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# SATELLITE PROPULSION SYSTEM ANALYSIS

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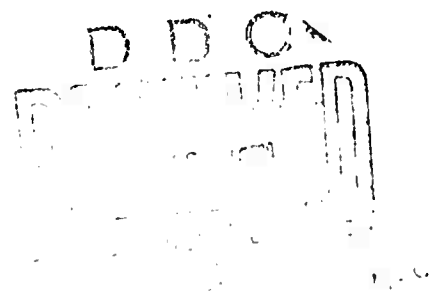
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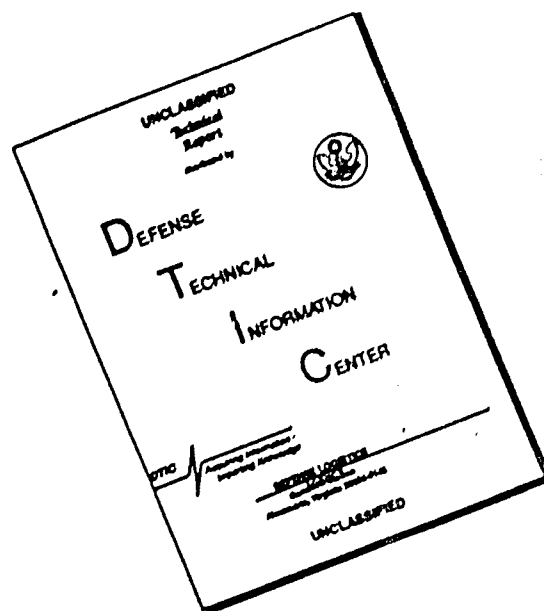
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## FOREWORD

This report summarizes work performed during a USAF in-house program under Project 3058, during the period October 1970 through June 1971.

The program was conducted by the Liquid Rocket Division of the Air Force Rocket Propulsion Laboratory. Captains Raymond D. Klopotek and Walden L. S. Laukhuf were the project engineers.

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This technical report has been reviewed and is approved.

JERRY N. MASON, Capt, USAF  
Chief, Subsystems Branch  
Liquid Rocket Division

## ABSTRACT

Propulsion systems were studied for post-1975 geosynchronous satellites that have stringent attitude and station maintenance requirements with mission durations of up to 10 years. Systems using catalytic monopropellant, nuclear-thermal monopropellant, chemical bipropellants and electric thrusters were studied and ranked according to several analysis areas which included propulsion system weight, system reliability and costs. Areas requiring further technology development are recommended on the basis of system rankings.

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# NOMENCLATURE

$A_1$	=	projected area in a plane normal to the line of sight, $\text{ft}^2$
$D$	=	diameter of satellite centerbody, feet
$g$	=	gravitational acceleration, $32.2 \text{ ft/sec}^2$
$I_{\text{bit}}$	=	impulse bit minimum, $\text{lb}_f\text{-sec}$
$I_{t_{\text{ac}}}$	=	total impulse for attitude control, $\text{lb}_f\text{-sec}$
$I_{t_{\text{AM}}}$	=	total impulse for attitude maintenance, $\text{lb}_f\text{-sec}$
$I_{t_c}$	=	total impulse for north-south stationkeeping, $\text{lb}_f\text{-sec}$
$I_{t_i}$	=	total impulse for east-west stationkeeping, $\text{lb}_f\text{-sec}$
$I_{t_{lc}}$	=	total impulse for limit cycling, $\text{lb}_f\text{-sec}$
$I_{t_s}$	=	total impulse for solar pressure corrections, $\text{lb}_f\text{-sec}$
$I_{xx}$	=	satellite moment of inertia about x axis, $\text{slug-ft}^2$
$I_{yy}$	=	satellite moment of inertia about y axis, $\text{slug-ft}^2$
$I_{zz}$	=	satellite moment of inertia about z axis, $\text{slug-ft}^2$
$J$	=	polar moment of inertia, $\text{slug-ft}^2$
$L$	=	length of satellite centerbody, feet
$M_{\text{CB}}$	=	mass of centerbody, $\text{lb}_m$
$M_c$	=	mass of satellite at end of propulsion maneuver, $\text{lb}_m$
$M_o$	=	mass of satellite at beginning of propulsion maneuver, $\text{lb}_m$
$M_{\text{sp}}$	=	mass of solar panels, $\text{lb}_m$
$P$	=	orbital period, degrees/day
$\Delta\dot{P}$	=	repositioning rate, degrees/day

# NOMENCLATURE (CONT'D)

$P$	propellant storage tank pressure, psi
$R$	propellant storage tank radius, inches
$r$	moment arm of thruster couple, feet
$R_{F_{LT}}$	large thruster feed system reliability
$R_{F_{ST}}$	small thruster feed system reliability
$R_{S_{LT}}$	total large thruster system reliability
$R_{S_{ST}}$	total small thruster system reliability
$R_{V-TH_{LT}}$	large thruster-valve combination reliability
$R_{V-TH_{ST}}$	small thruster-valve combination reliability
$T$	storage tank thickness, inches
$t_m$	mission duration, years
$V_o$	nominal orbital velocity, ft/sec
$\Delta V$	change in satellite velocity, ft/sec
$\Delta V_{rep}$	change in velocity for repositioning, ft/sec
$X$	solar CP-CG offset, feet
$X_{CB}$	- for rectangular centerbody, the x-axis dimension, feet
$X_{SP}$	height of solar panel (distance parallel to centerbody, feet
$Y_{CB}$	for rectangular centerbody, the y-axis dimension, feet
$Y_{SP}$	length of solar panel (distance perpendicular to centerbody), feet
$Z_{CB}$	for rectangular centerbody, the z-axis dimension, feet
	leadband half-angle, degrees

# NOMENCLATURE (CONT'D)

- $\epsilon_c$  = drift in satellite position cross-track, nm
- $\epsilon_i$  = drift in satellite position in-track, nm
- $\theta_{\min}$  = satellite minimum achievable average angular rate, deg/sec
- $\rho$  = propellant storage tank material density, lb/in<sup>3</sup>
- $\sigma_y$  = yield stress of storage tank material, psi



## SECTION I

### INTRODUCTION

The task of evaluating future attitude control propulsion development programs for satellite applications is unwieldy due to the proliferation of systems concepts over the past 10 years. Since budgetary constraints limit the amount of dollars for new technology efforts, a method for selecting the most promising areas of future satellite propulsion work is needed. Past evaluation methods have employed fragmented examinations of various engine performance parameters such as specific impulse, pulse centroid repeatability and minimum impulse bit (Reference 1). No recent comparisons on a total system design basis for a specific mission have been made. Only one other satellite system study has been undertaken at the Air Force Rocket Propulsion Laboratory (AFRPL). This study was completed on 20 May 1968 by Mr. E. C. Barth. It was entitled "Applications of DART for Space Relay and Data Management Satellite."

The present study uses an advanced geosynchronous mission model having stringent attitude and station maintenance requirements to compare 16 satellite propulsion systems, in various phases of development, against such important system design parameters as propulsion system weight, system reliability and costs. These ranged from the conventional monopropellant hydrazine thrusters to more sophisticated electric ion thrusters.

## SECTION II

### APPROACH

The construction of a post-1975 satellite mission model was based primarily upon existing model availability. From the several satellite models postulated for geosynchronous orbit, the Air Force's Space and Missile System Organization (SAMSO) model pertaining to the class of satellites referred to as "SYNCSATS" was chosen as the framework for this study (Reference 2). SYNCSATS provide for a wide variety of commercial and military missions, including communication relays, navigation aids, and meteorological and strategic reconnaissance.

So that a large variety of satellite propulsion systems could be readily evaluated, a computer program (see Appendix A) using the SYNCSAT mission model was developed to calculate total propulsion system weight, propellant tank sizing and mission total impulse requirements. The program is also designed to size and weigh the satellite centerbody and solar panels and to compute the available on-board electrical power. Some of the SYNCSAT parameters which may be varied are the satellite life, initial gross weight, initial angular momentum, centerbody bulk density and repositioning rate.

In conjunction with the weight computer program, a reliability and cost study for each propulsion system design was undertaken. Reliability data were extracted from a recent Jet Propulsion Laboratory (JPL) report (Reference 3) which arrived at quantitative satellite propulsion component reliabilities based on a review of existing reliability studies and reported component reliability and failure rate values. Reliabilities for noncyclic components were based on a 1-year mission duration. Improving reliability figures through the use of redundancy was not assessed in this study. It is to be noted that a quantitative ranking of the components is difficult since reliability numbers for propulsion system components do not have

the extensive statistical failure rate data typical of electronic components.

Development cost data for advanced propulsion systems are very difficult to obtain. Moreover, a significant portion of the development cost is expended for flight qualification. This dichotomy between development and system engineering groups compounds the total cost estimate. Instead of expending many hours in an attempt to acquire every bit of cost data, a rough cost estimate for existing propulsion systems was undertaken by using available figures from reported development and flight qualified systems. Postulated propulsion system costs were then extrapolated from these existing estimates. Although the anticipated monetary inflationary rate will alter cost estimates for post-1975 propulsion systems, the figures used for this study are based on 1971 dollars. In addition to a quantitative evaluation of system weight, reliability and cost, other tradeoff areas were qualitatively evaluated. These included plume effects, integration problems, design flexibility and ground handling requirements.

## SECTION III

### ANALYSIS

#### A. POST-1975 SYNCATS MISSION MODEL

##### 1. Introduction

One of the most useful satellite orbits is the "earth-synchronous" or "geosynchronous" orbit, i.e., a circular orbit in the equatorial plane with an orbital period of one sidereal day. A satellite placed in such an orbit will (ideally) remain fixed in the sky, relative to an observer on the earth. The orbital characteristics for a "geosynchronous" orbit are:

Semi-major axis,	$a$	=	22,808.5 nm
Eccentricity,	$e$	=	0
Inclination,	$i$	=	0
Period,	$P$	=	24 hours

The class of satellites having the above orbital parameters are referred to as "SYNCATS," and cover a wide variety of useful missions, both commercial and military. Many of these missions will require extremely close pointing accuracy and/or precise stationkeeping. Such requirements, coupled with a long mission duration, tax the capabilities of current propulsion technology.

A three-axis active attitude control system (ACS) was chosen for the SYNCAT in preference to spin-stabilized or gravity gradient systems. A fully stabilized satellite presents the most demanding propulsion requirements, offers a significantly higher on-board electrical power

capacity through the use of a one-degree-of-freedom, sun-oriented solar array, and can meet the close stationkeeping and tight attitude control specifications. Furthermore, the three-axis active control system does not demand the rapid pulsing capability of a spin-stabilized spacecraft and thus can utilize a wider range of propulsion concepts.

## 2. Satellite Geometry

An inertial model of a SYNCSAT spacecraft was formulated to permit propulsion system sizing and power allocation. The model does not represent any specific design in this family of prospective SYNCSATS, but merely a consistent set of dimensions and inertias. Geometrically, the spacecraft centerbody may assume a cylindrical, spherical or rectangular shape. The one-degree-of-freedom, articulated solar array takes the form of two rectangular solar panels symmetrically deployed on either side of the centerbody, which contains the remaining equipment. The spacecraft configuration is shown in Figure 1. This figure shows the centerbody as a cylinder. The spacecraft model incorporates both high-thrust engines of 5-pound thrust and low thrusters of less than 1-pound thrust.

For the two solar panels, an ideal specific weight is required. Combining this figure with a percent life degradation factor yields an array specific weight. A specific surface area must also be assumed.

To arrive at dimensional and inertial characteristics for the model, it was first necessary to size the solar array. The assumed available on-board power can be given as a function of initial gross weight according to the equation:

$$\text{On-Board Power (w)} = -400 + 1.25 \times \text{Initial Gross Weight (lb}_m\text{)}$$

(III-1)

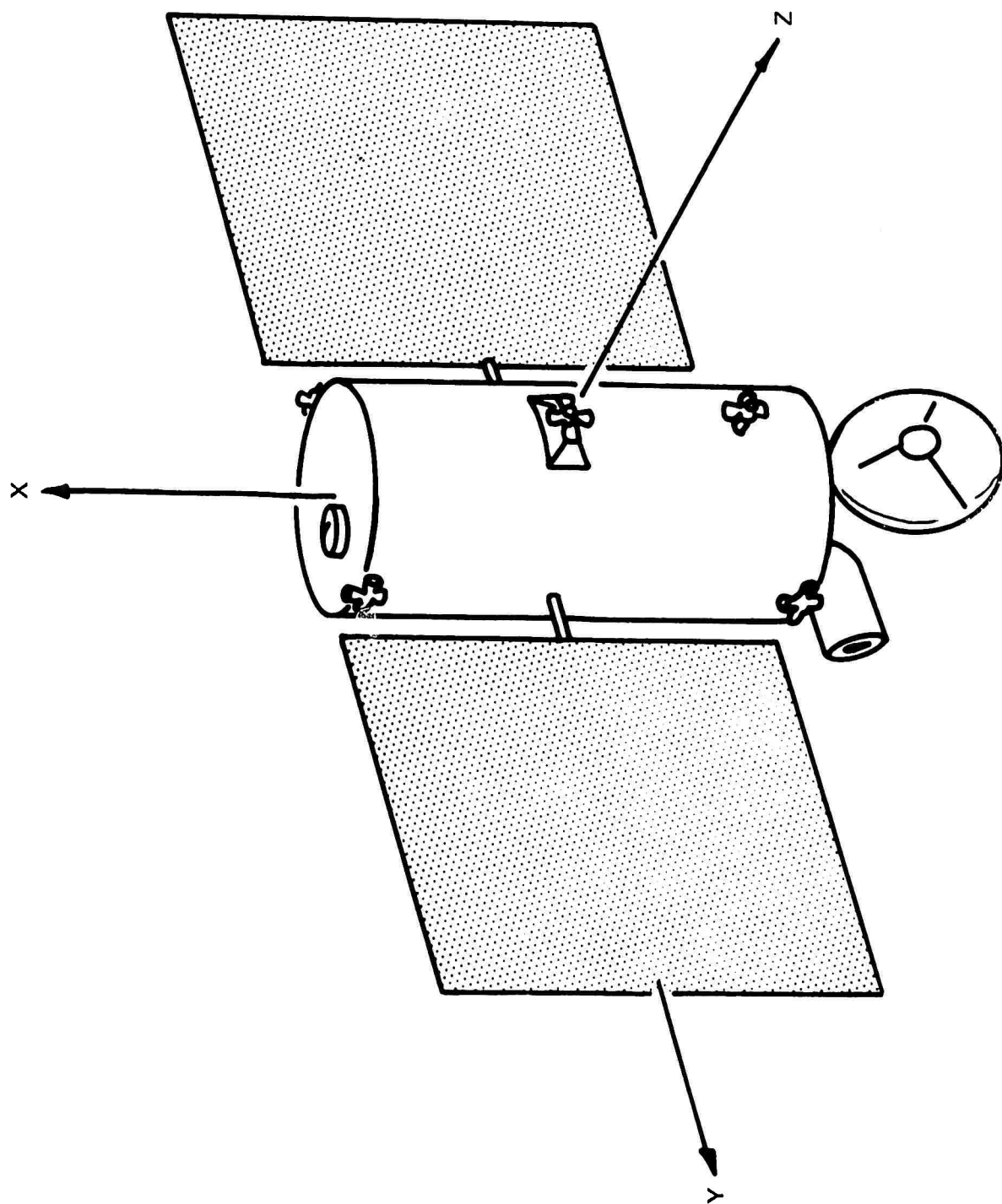


Figure 1. Spacecraft Inertial Model

Once the on-board electric power is known, then the weight and size of the two rectangular solar panels to supply this power are calculated. From the centerbody weight, density and L/D configuration, the dimensions of the centerbody are obtained. Next, calculated moments of inertia for the three principal axes are developed.

For this study, the following design information was used. The initial gross weights were assumed to be 2000 lb<sub>m</sub> and 3000 lb<sub>m</sub>. The centerbody assumed a cylindrical shape with an L/D of 2:1. Existing spacecraft indicate that a bulk density of 20 lb<sub>m</sub>/ft<sup>3</sup> is representative for the centerbody. The solar panels were taken to be square with an ideal specific weight of 88 lb<sub>m</sub>/kw. The percent life degradation was 80 percent and the solar panels were assumed to have a specific surface area of 100 ft<sup>2</sup>/kw.

For the two initial gross weights assumed, Table I presents spacecraft geometry data.

TABLE I. SATELLITE MODEL GEOMETRY

Initial Gross Weight (lb <sub>m</sub> )	2000	3000	
On-board Electric Power (kw)	2.10	3.35	
Centerbody Diameter (feet)	3.833	4.375	
Centerbody Length (feet)	7.666	8.75	
Centerbody Weight (lb <sub>m</sub> )	1769.0	2631.5	
Solar Array Area (ft <sup>2</sup> )	210.0	234.8	
Side of One Solar Panel (feet)	10.25	12.94	
Maximum Projected Area (ft <sup>2</sup> )	239.4	373.3	
Moments of Inertia (slug-ft <sup>2</sup> ) (Solar Panels Deployed)	I <sub>xx</sub>	378.3	889.3
	I <sub>yy</sub>	382.2	779.0
	I <sub>zz</sub>	800.6	1796.8

### 3. Mission Requirements

With the model spacecraft established, a consistent set of maneuver and control requirements were taken from Reference 2. The propulsive functions involved are of four types:

Initial positioning  
Attitude maintenance  
Station maintenance  
Repositioning

Propulsion requirements for the foregoing maneuver and control functions are now described in detail.

#### a. Initial Positioning (Injection Error Corrections)

The initial positioning errors are primarily caused by the launch vehicle. Upon separating from the booster, the spacecraft will have a residual rate (tumble) in each axis which must be nulled. It will also have a terminal velocity and position error to be corrected. Eccentricity and inclination errors need to be reduced only if the resulting oscillation is greater than the allowable deadband.

Based upon existing booster performance, a  $\Delta V$  allowance of 50 ft/sec for position and velocity error correction, and a 1 deg/sec residual rate correction in each axis would be nominal. For this study, the inclination and eccentricity errors were assumed tolerable, and the total impulse required to correct for the initial tumble in all three axes was taken to be a constant value of 23 lb<sub>f</sub>/sec for both spacecraft weights.



b. Attitude Maintenance

Attitude maintenance comprises the limit cycling within some prescribed deadband and the correction of disturbance torques. The primary contributor of disturbance torques is solar pressure. Assuming unit reflectivity and normal incidence, the total corrective impulse which must be supplied to the spacecraft in  $t_m$  years is (Reference 2):

$$I_{t_s} = 5.91 \cdot t_m \sum_j \left( \frac{A_1 X}{r^2} \right)_j \text{ lb}_f\text{-sec} \quad (\text{III-2})$$

where:  $A_1$  = total satellite projected area in a plane normal to the line of sight to the sun ( $\text{ft}^2$ )

where the summation is carried out for the two axes involved. Appropriate values for the solar CP-CG offset,  $X$ , for different spacecraft were taken as in Reference 2:

$$\text{so that } \sum_r \frac{X}{r} = \sum \frac{\text{CP-CG OFFSET}}{\text{Moment Arm}} = 0.35 \text{ in all cases.}$$

The impulse involved in limit cycling depends upon a number of factors. Maximum propellant consumption occurs in a symmetric (undisturbed) limit cycle. Although symmetric limit cycling is not truly representative for this type of spacecraft, the conservatism implicit in such an assumption does not significantly distort the results and greatly simplifies the calculations. The primary parameters in the total impulse

requirements are the half-angle of the deadband,  $\delta$ , and the size of the minimum impulse bit,  $I_{bit}$ . The total limit cycle impulse delivered in  $t_m$  years is (Reference 2):

$$I_{t_{lc}} = \frac{I_{bit}^2 t_m}{\delta} \sum_k \left( \frac{r}{J} \right)_k \text{ lb}_f\text{-sec} \quad (\text{III-3})$$

where

$r$  = moment arm of thruster couple (feet)  
 $J$  = polar moment of inertia (slug-ft<sup>2</sup>)

down to some minimum achievable average angular rate,  $\dot{\theta}_{min}$ , at which point the rate limit impulse is (Reference 2):

$$I_{t_{lc_{min}}} = 4 \frac{\dot{\theta}_{min} t_m}{\delta} \sum_k \left( \frac{J}{r} \right)_k \text{ lb}_f\text{-sec} \quad (\text{III-4})$$

Deadband angles typically range from  $\pm 0.125$  degree in coarse mode control to  $\pm 0.100$  degree in fine mode control. This study assumed a minimum achievable average angular rate of  $2 \times 10^{-4}$  deg/sec and the deadband angle of  $\pm 0.125$  degree.

For satellites with relatively large surface areas and long mission durations, the effects of micrometeoroid bombardment must be assessed. Using probability theory based on the possible case, Aerospace (Reference 2) has shown that the predictable impulse for micrometeoroid impact correction is negligible. The unpredictable impulse requirement due to a large and improbable impact must be provided in the "contingency" impulse.

Other disturbances, such as torques imparted by the friction in moving telescopes or antennae, gravity gradient and earth magnetic field torques, and coupling of translation thrust into the attitude control axes caused by thruster misalignment with respect either to the spacecraft center of mass or to each other, could not be accurately estimated without a more detailed and sophisticated model. It was therefore decided to apply a generous contingency of 50 percent to the total of solar and limit cycle impulse allocations. Thus, the attitude control total impulse was assumed to be (Reference 2):

$$I_{t_{ac}} = 1.5 \left[ I_{t_s} + I_{t_{lc}} \right] \text{ lb}_f\text{-sec} \quad (\text{III-5})$$

#### c. Station Maintenance

The bulk of the spacecraft's propulsion requirement is for station-keeping. A real earth SYNCSAT tends to drift from its initial position radially, longitudinally and latitudinally (cross-track). These drifts are caused by the triaxiality (asphericity) of the earth and by the gravitational perturbations due to the sun and the moon.

At synchronous altitude, the observable angular deviation due to radial drift is negligible in any foreseeable mission. Thus, only in-track (east-west) and cross-track (north-south) stationkeeping are required. Table II lists the major perturbations on a 24-hour equatorial circular orbit which cannot be corrected by initial injection bias (as reported in Reference 4).

TABLE II. GEOSYNCHRONOUS ORBIT PERTURBATIONS

Perturbation Cause	Direction	Period	Displacement	$\Delta V/\text{yr}$
Zonal Harmonics	-	-	-	-
Tesseral Harmonics	In-track	Secular	$t^2$ dependent	7.15
Solar-Lunar	Cross-track	Secular	5630 ft/day	150
Solar-Lunar	In-track ( $\epsilon_i$ )	2 years	$\pm 14.8$ nm	-
Solar-Lunar	Cross-track ( $\epsilon_c$ )	24 hours	$\pm 8.9$ nm	-

A zonal harmonic results from the terms in the gravitational potential of the earth that are dependent on latitude only and are therefore symmetrical about the equator. This is a result of the fact that the earth is not a perfect sphere. However, drifts caused by this perturbation may be corrected by injection bias. Tesseral harmonics are those resulting from the aspherical gravitation field or inhomogeneous mass distributions of the earth. Hence, one area of the earth will have a greater gravitational attraction for a satellite than another area. These areas are not symmetrical about the equator and thus produce an east-west drift upon a satellite. The solar-lunar perturbations result from the pull of the sun and the moon on the earth. A secular perturbation is one which is not periodic but is a constant perturbation dependent, for example, on the time in orbit. The periodic solar-lunar perturbations need not be corrected if the displacement shown is acceptable.

If the tolerable drift amplitude for stationkeeping is taken to be greater than or equal to the periodic perturbations shown in Table II, i.e.,  $\epsilon_i \geq 14.8$  nm and  $\epsilon_c \geq 8.9$  nm (referred to as the critical ellipsoid), then an annual  $\Delta V$  increment of about 157 ft/sec, dominated by the cross-track correction, is required. However, if a "fine" stationkeeping mode, i.e.,  $\epsilon_i < 14.8$  nm and  $\epsilon_c < 8.9$  nm, is desired, the value for  $\Delta V$  jumps to

about 635 ft/sec/yr. This study will only consider an annual  $\Delta V$  increment of 157 ft/sec for stationkeeping.

To account for coupling of thrust into the attitude control axes during the attitude maintenance maneuvers, 3 percent of the stationkeeping total-impulse requirement was allotted for this purpose. Thus, the attitude maintenance total impulse was taken as (Reference 2):

$$I_{t_{am}} = 1.03 \left[ I_{t_i} + I_{t_c} \right] \text{ lb}_f\text{-sec} \quad (\text{III-6})$$

#### d. Repositioning

Post-1975 SYNCATS must be capable of covering any global region. This implies that the satellite has the capability to perform transfers of up to 180 degrees in longitude. For any given satellite thrust-to-weight ratio and change in satellite longitudinal position, a minimum time for repositioning can be determined. The velocity increment required is a function only of the repositioning rate. The total  $\Delta V$  required per repositioning is given by the following equation:

$$\Delta \dot{P}_{rep} = \frac{2 V_o}{3} - \frac{\Delta \dot{P}}{P} \quad (\text{III-7})$$

$$\begin{aligned} V_o &= \text{nominal orbital velocity (ft/sec)} \\ P &= \text{orbital period (deg/day)} \\ \Delta \dot{P} &= \text{repositioning rate (deg/day)} \end{aligned}$$

For the mission study of this report, a one-time satellite repositioning maneuver was assumed to be representative for a post-1975 SYNCAT, and repositioning rate of 15 deg/day was used. The total  $\Delta V_{rep}$  required for this maneuver using equation III-7 is 280 ft/sec.

The most efficient method for repositioning is to place the satellite into an orbit with a period greater or less than 24 hours, causing a westward or eastward, respectively, drift. For example, the drift is 15 deg/day for an orbit with a 25-hour period and requires a  $\Delta V$  expenditure of approximately 280 ft/sec for both high- and low-thrust devices. Using this technique, repositioning requires from a few days to approximately 2 weeks.

A summary of the mission requirements used in this study is given in Table III.

TABLE III. MISSION REQUIREMENTS

Function	$\Delta V$ Requirement	ACS Requirement
Initial Positioning		
Position/Velocity Error	50 ft/sec	
Tip-off Rate, Each of Three Axes		23 lb <sub>f</sub> -sec
Stationkeeping	157 ft/sec/yr (E-W/N-S of $\pm 8.9 \times 15$ nm)	
Attitude Maintenance		$\pm 0.125$ -degree deadband, $2 \times 10^{-4}$ deg/sec average rate
Repositioning	280 ft/sec	

#### B. SYNCSAT PROPULSION SYSTEMS

Sixteen different combinations of high and low thrusters were incorporated into the spacecraft model and evaluated. The high-thrust engines were 5 pounds and the low thrusters were less than 1 pound. The large thrusters were used for initial positioning and repositioning, while attitude

maintenance was performed with the small thruster. The thruster (i.e., large or small) which had the highest performance was used for stationkeeping.

A listing of the 16 propulsion systems evaluated is presented below:

<u>5 lb<sub>f</sub> Thruster</u>	<u>Small Thruster</u>
1. N <sub>2</sub> H <sub>4</sub> Catalytic	N <sub>2</sub> H <sub>4</sub> Catalytic
2. N <sub>2</sub> H <sub>4</sub> Catalytic	N <sub>2</sub> H <sub>4</sub> Plenum
3. N <sub>2</sub> H <sub>4</sub> Catalytic	N <sub>2</sub> H <sub>4</sub> Electrolytic
4. N <sub>2</sub> H <sub>4</sub> Catalytic	N <sub>2</sub> H <sub>4</sub> Resistojet
5. N <sub>2</sub> H <sub>4</sub> Catalytic	N <sub>2</sub> H <sub>4</sub> Radioisotope
6. N <sub>2</sub> H <sub>4</sub> Catalytic	DART
7. N <sub>2</sub> H <sub>4</sub> Catalytic	Cesium Ion
8. N <sub>2</sub> H <sub>4</sub> Catalytic	Colloid
9. N <sub>2</sub> H <sub>4</sub> Catalytic	Hg Pulsed Plasma
10. DO Radioisotope	DO Radioisotope
11. DO Radioisotope	Colloid
12. H <sub>2</sub> O Electrolysis Bipropellant	H <sub>2</sub> O Electrolysis Bipropellant
13. H <sub>2</sub> O Electrolysis Bipropellant	Colloid

Dioxyamine

<u>5 lb<sub>f</sub> Thruster</u>	<u>Small Thruster</u>
14. $\text{N}_2\text{O}_4/\text{N}_2\text{H}_4$ Bipropellant	$\text{N}_2\text{H}_4$ Plenum
15. $\text{ClF}_5/\text{N}_2\text{H}_4$ Bipropellant	$\text{N}_2\text{H}_4$ Plenum
16. DART	DART

The following subsections provide a conceptual design schematic for each of the 16 propulsion systems. System description and performance data are also included.

#### 1. Hydrazine Catalytic/Hydrazine Catalytic

The development of the Shell 405 catalyst in 1963 permitted the design of hydrazine thrusters capable of a large number of restarts without requiring the use of catalyst bed heaters or an oxidizer injection system for initiation of hydrazine decomposition. Since then, monopropellant hydrazine thrusters have become the "standard" spacecraft propulsion system for missions which do not have stringent orientation requirements and are not marginal on weight. Hydrazine has excellent storability, good compatibility with most engineering materials and is capable of repeated pulse operation.

##### a. 5-lb<sub>f</sub> Thruster

Steady-state performance for the 5-pound hydrazine thruster, such as in Figure 2, was based upon 55 percent  $\text{NH}_3$  dissociation, on an area ratio of 40:1 and upon 97 percent engine efficiency, giving 230 seconds of delivered specific impulse. This performance represents nearly the maximum achievable with hydrazine. Some hydrazine thrusters have demonstrated steady-state firings exceeding 2 hours. The only required power is that necessary to operate the propellant valves. However, in



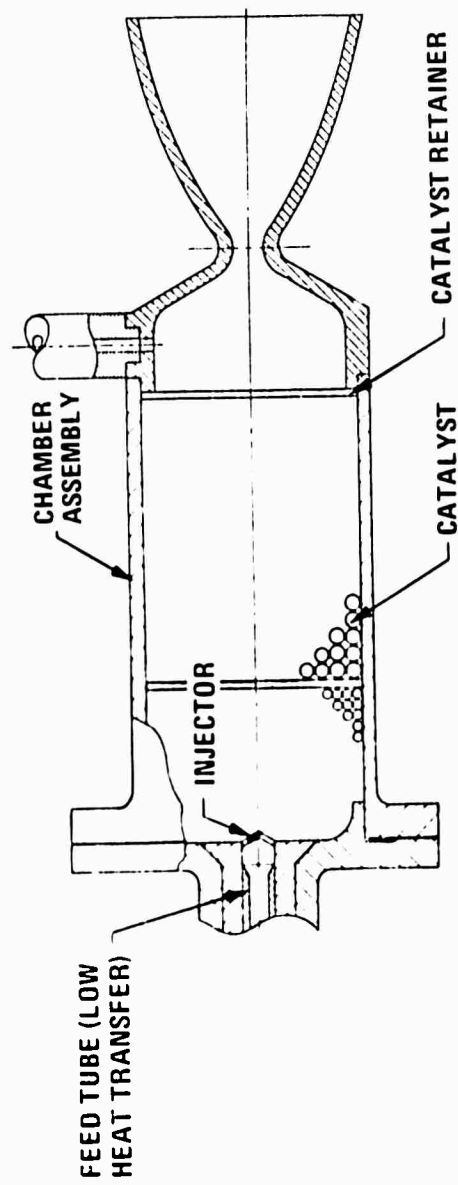


Figure 2. Catalytic Hydrazine Thruster

certain installations, the low freezing point of hydrazine ( $33^{\circ}\text{F}$ ) necessitates the incorporation of a 2- to 10-watt heater on each thruster.

b. 0.1-lb<sub>f</sub> Thruster

Pulse-mode performance of the small thruster was based upon the same assumptions as those for the large thruster. Assuming that heaters would be used on the catalyst pack to maintain temperature above  $60^{\circ}\text{F}$ , and using a minimum impulse bit of  $4 \times 10^{-3}$  lb-sec, a specific impulse of 200 seconds is achievable. Although no flight-qualified 0.1-lb<sub>f</sub> thrusters have been built, a present NASA/Goddard development effort for the Applied Technology Satellites (ATS), Models F & G, will provide this technology. Hydrazine thrusters have demonstrated pulsing capability on the order of 1-million hot starts. Several thousand cold starts should be realizable without significant performance degradation. (Reference 3).

c. System Schematic

Figure 3 shows the system schematic.

2. N<sub>2</sub>H<sub>4</sub> Catalytic/N<sub>2</sub>H<sub>4</sub> Plenum

This hybrid propulsion system is a modification of the all-hydrazine catalytic system. Hydrazine plenum systems have been developed and flight qualified by Rocket Research Corporation and TRW Systems. For this design, the low-level thrusters are supplied gas from a single catalytic hydrazine gas generator which feeds an accumulator or plenum. The only system problem encountered with this hybrid system has been that of maintaining a cool plenum temperature during a long pulse duty cycle (Reference 3).

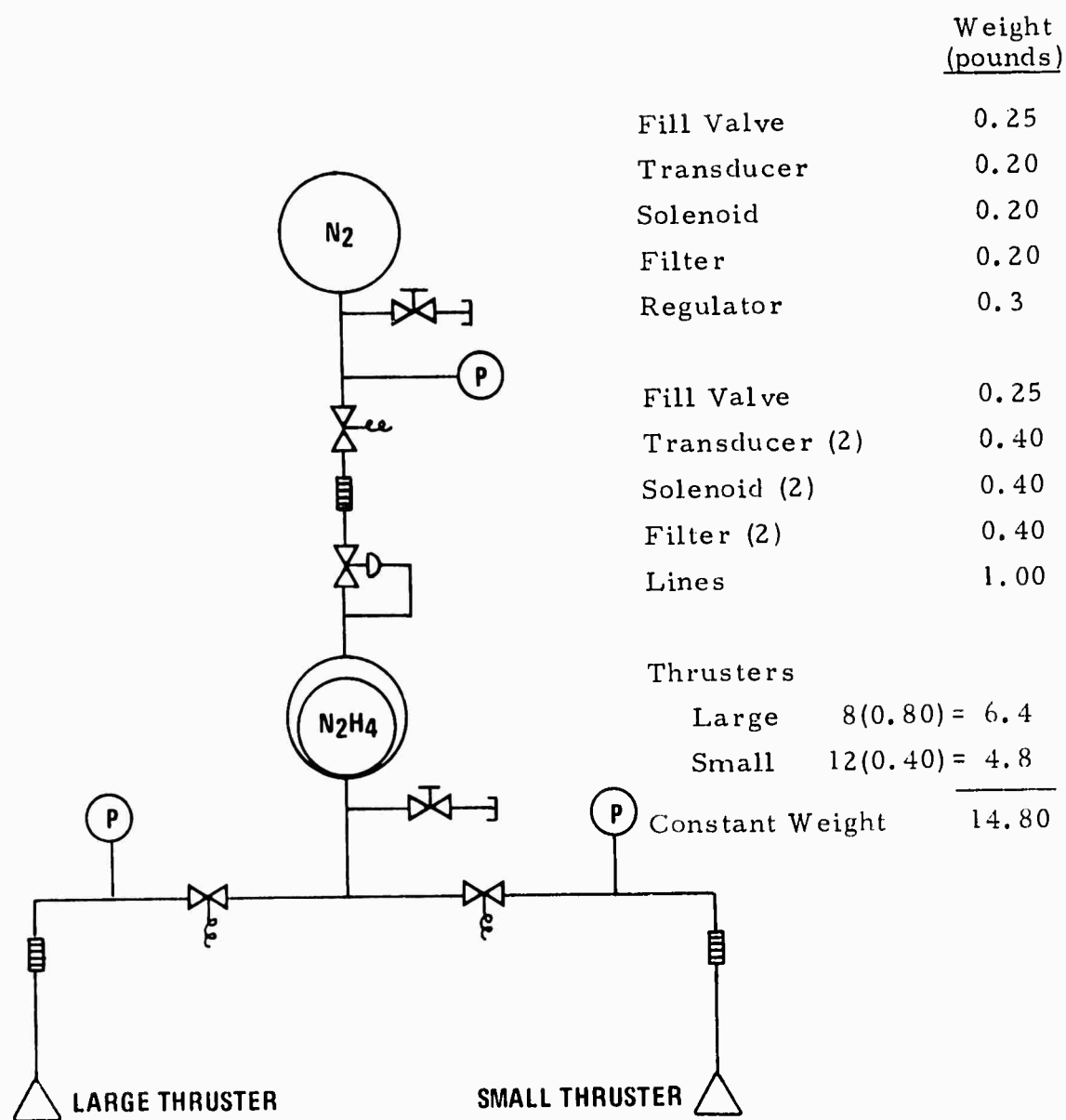


Figure 3. System Schematic for  $N_2H_4$  Catalytic- $N_2H_4$  Catalytic

a. 5-lb<sub>f</sub> Thruster

The large hydrazine catalytic thruster is identical to that described in Section III.B.1. All performance numbers remain unchanged.

b. 0.050-lb<sub>f</sub> Plenum Thrusters

The catalytic hydrazine gas generator uses Shell 405 catalyst and feeds a plenum tank having a nominal 35-psia pressure. Specific impulse for the 50-millipound thrusters is taken to be a constant 110 seconds for this study. Actual performance data for an N<sub>2</sub>H<sub>4</sub> cold gas plenum varies between 95 and 110 seconds depending upon the gas temperature. If individual heaters are used on all low-level thrusters, then the specific impulse will vary between 114 and 132 seconds, again depending upon the plenum gas temperature. A minimum impulse bit of  $5 \times 10^{-4}$  lb<sub>f</sub>-sec was used.

c. System Schematic

Figure 4 shows the system schematic.

3. N<sub>2</sub>H<sub>4</sub> Catalytic/N<sub>2</sub>H<sub>4</sub> Electrolytic Ignition

The search for an efficient method of initiating and continuing the decomposition of hydrazine without the use of a scarce catalyst has led researchers to the concept of electrolytic ignition. The Air Force Rocket Propulsion Laboratory (AFRPL) first determined the feasibility of this approach through a contractual program with the Dynamic Science Corporation in 1969-1970 (Contract F04611-69-C-0048, Final Report AFRPL-TR-69-247). Presently, the United Aircraft Corporation Research Laboratory is under contract (F04611-70-C-0070) to AFRPL for development of an electrolytic ignition cell for use in a 0.1-lb<sub>f</sub> thruster.

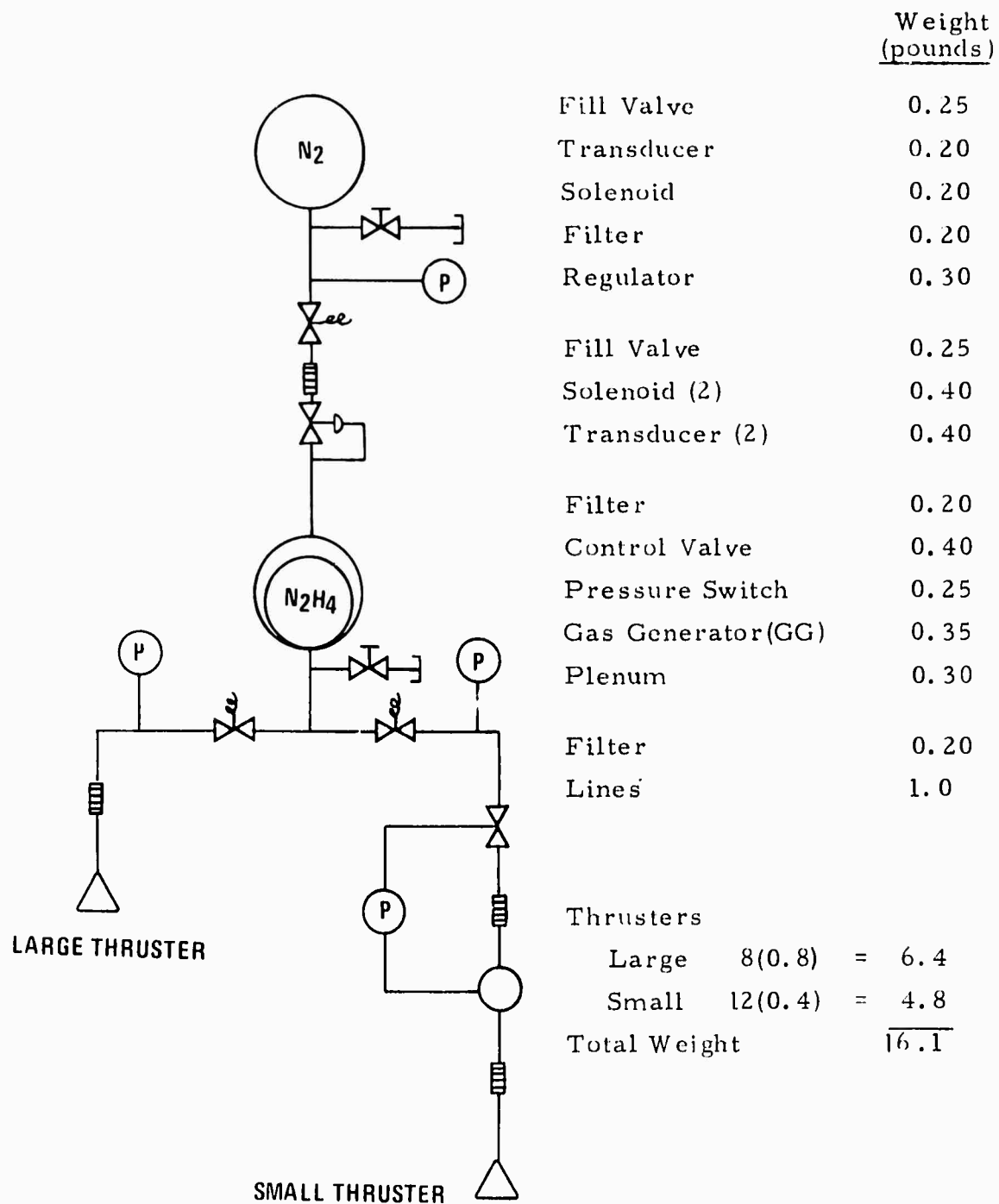


Figure 4. System Schematic for  $N_2H_4$  Catalytic- $N_2H_4$  GG Plenum

Fabrication and testing of this cell have not yet begun. Since no test data are available, all performance numbers are to be considered as "best" estimates and will have to be revised in the future.

a. 5-lb<sub>f</sub> Thruster

The large hydrazine catalytic thruster is identical to that described in Section III.B.1. All performance numbers remain the same.

b. 0.1-lb<sub>f</sub> Thruster

This study postulates a 0.1-lb<sub>f</sub> hydrazine electrolytic ignition thruster having a pulse mode specific impulse of  $I_{sp} = 220$  seconds and a minimum impulse bit of  $5 \times 10^{-3}$  lb<sub>f</sub>-sec. This size of low-level thruster will require approximately 15 watts of electrical power excluding that required for the valve. No life or reliability data are available.

c. System Schematic

The system schematic is shown in Figure 5.

4. N<sub>2</sub>H<sub>4</sub> Catalytic/N<sub>2</sub>H<sub>4</sub> Resistojet

The hydrazine resistojet has been under development by both AVCO (NAS 5-21080) and TRW. AVCO has built and tested a number of prototype thrusters for NASA/Goddard Space Flight Center using a porous ceramic injector configuration. Test data have shown that  $I_{sp}$  is

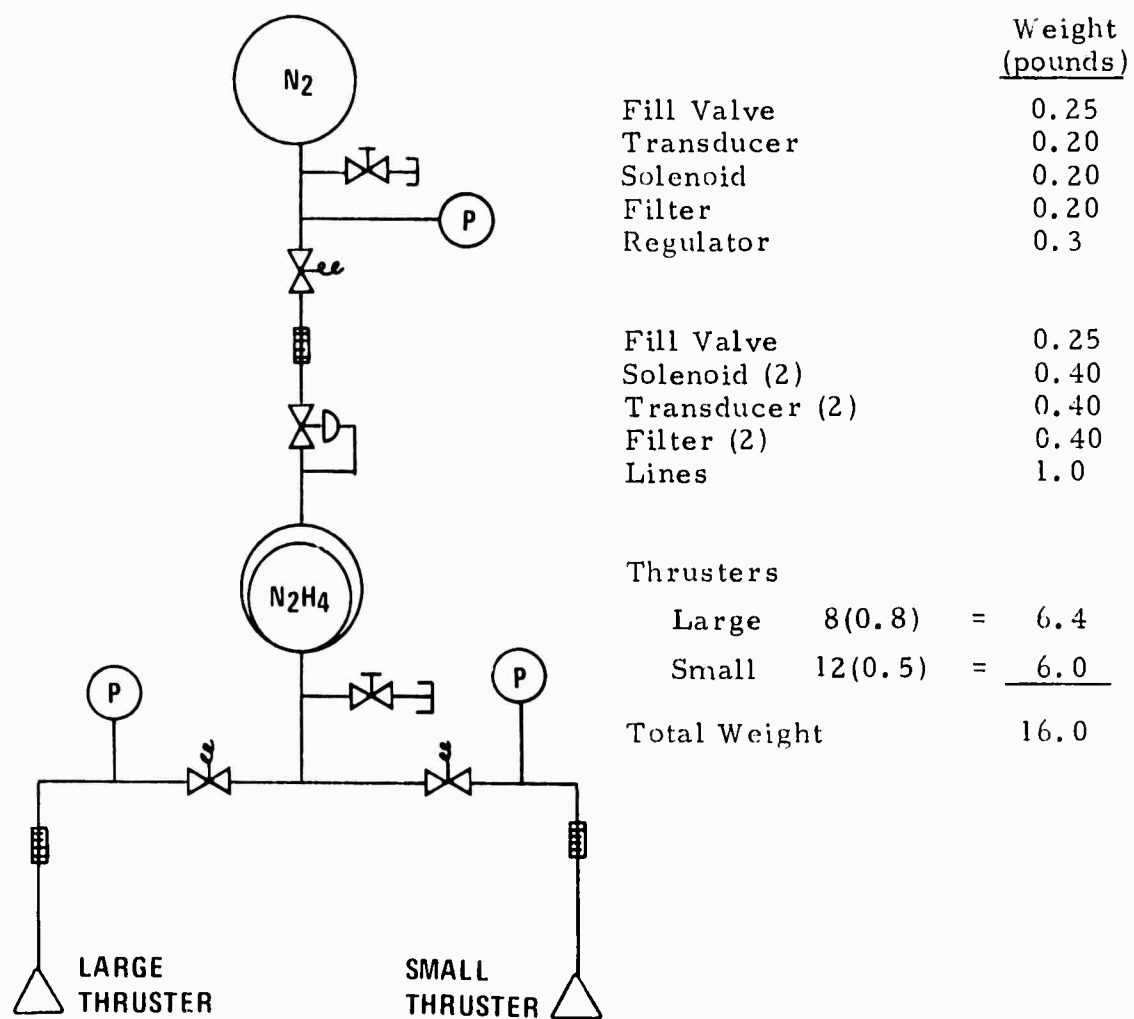


Figure 5. System Schematic for  $N_2H_4$  Catalytic- $N_2H_4$  Electrolytic

a strong function of thrust level ( $N_2H_4$  flow rate), so that the designer must be careful of his performance numbers. AVCO prototype data are:

Thrust ( $lb_f$ )	$I_{sp} \left( \frac{lb_f \cdot sec}{lb_m} \right)$
$2.4 \times 10^{-3}$	120
$4.6 \times 10^{-3}$	155
$7.1 \times 10^{-3}$	177
$9.5 \times 10^{-3}$	190
$12.0 \times 10^{-3}$	200
$14.4 \times 10^{-3}$	206
$16.8 \times 10^{-3}$	210

Specific power for the AVCO prototype thruster is approximately 2 W/mlb<sub>f</sub> (10 mlb<sub>f</sub>). TRW has completed the preliminary development of a 0.01-lb<sub>f</sub>-thrust hydrazine resistojet thruster for both pulsed and steady-state operation. Reproducible impulse bits based upon pulse widths as short as 20 milliseconds have been demonstrated.

The pulsed mode specific impulse is 180 seconds; steady-state operation results in a delivered specific impulse of 200 seconds. The total power input for a 0.010-lb<sub>f</sub> thrust system is less than 5 watts, excluding the valve power.



a. 5-lb<sub>f</sub> Thruster

The large hydrazine catalytic thruster is identical to that described in Section III.B.1.

b. 0.050-lb<sub>f</sub> Thruster

Contractor in-house programs have arrived at a new wall injection prototype thruster design incorporating a spiral-wound heater element (Figure 6). This thruster has a moderately high chamber pressure of 8.5 atmospheres and delivers 235 seconds of steady-state specific impulse. The hydrazine resistojet can be pulsed as low as 50 milliseconds and deliver an average of 190 seconds Isp. These values yield a minimum impulse bit of  $2.5 \times 10^{-3}$  lb<sub>f</sub>-sec. The new prototype thruster requires 5 watts for approximately 1 minute prior to ignition. This electrical input raises the wall temperature to 1000°F.

c. System Schematic

The system schematic is shown in Figure 7.

5. N<sub>2</sub>H<sub>4</sub> Catalytic/N<sub>2</sub>H<sub>4</sub> Radioisotope

Both General Electric Company and TRW have developed radioisotope thrusters using either NH<sub>3</sub> or H<sub>2</sub> as the propellant. Very little technology has been expended on a hydrazine radioisotope thruster. Since N<sub>2</sub>H<sub>4</sub> decomposes exothermally, the isotope power required is considerably reduced from that of an ammonia radioisotope thruster. Therefore, thruster inert weight and power required will be less for the hydrazine system. To achieve long life, capsule temperatures will be 2000°F or less. The design of such a thruster will be very similar to the DART system in that there is a radioisotope, re-entry heat shield, propellant flow tubes, and thermal insulation (Figure 8).

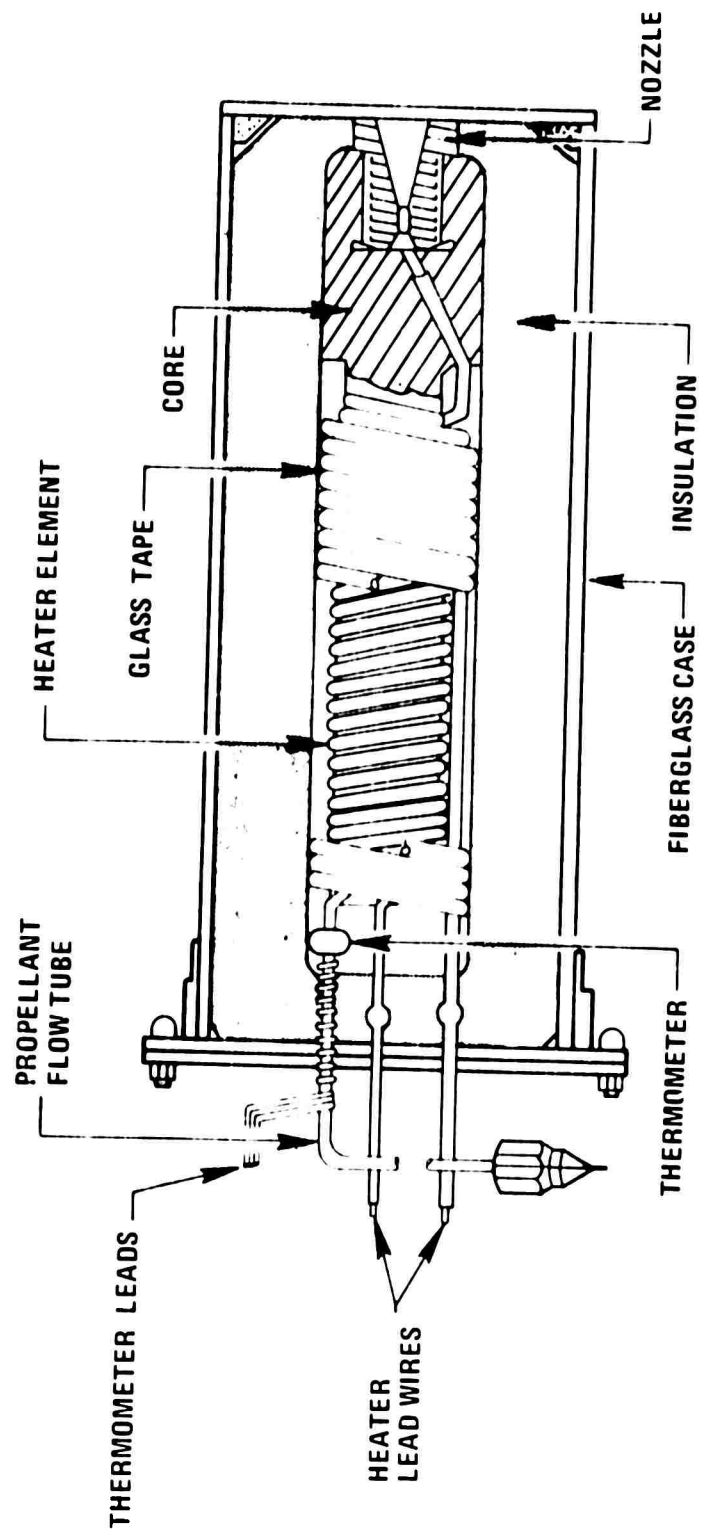
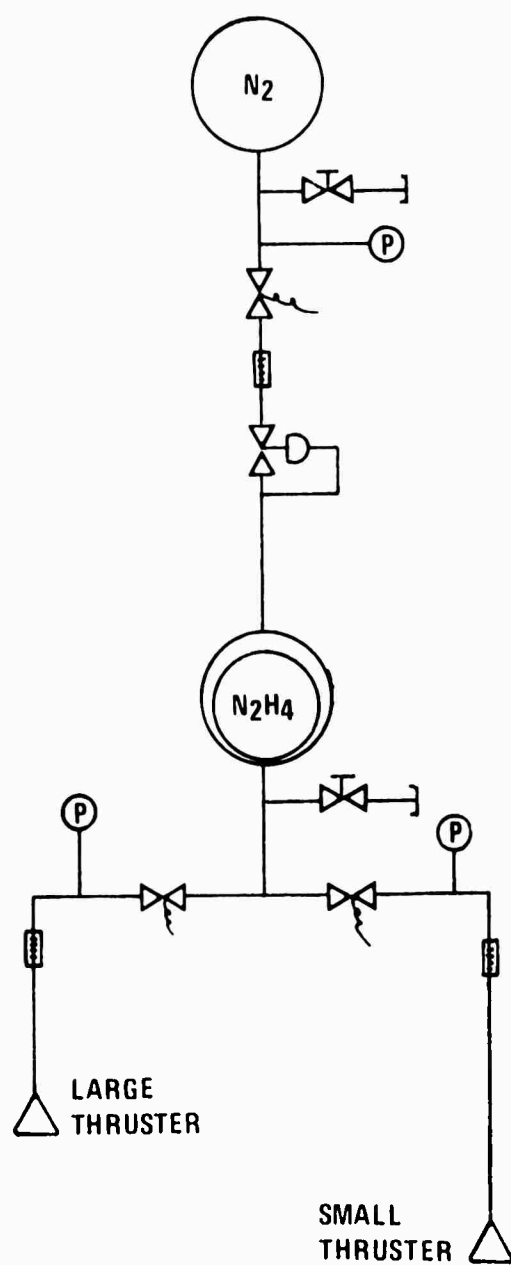


Figure 6.  $N_2H_4$  Resistojet Thruster



	Weight (pounds)
Fill Valve	0.25
Transducer	0.20
Solenoid	0.20
Filter	0.20
Regulator	0.3
Fill Valve	0.25
Solenoid (2)	0.40
Transducer (2)	0.40
Filter (2)	0.40
Lines	1.0
Thrusters	
Large    8(0.8)	= 6.4
Small    3(0.45)	= 1.35
Total Weight	<hr/> 11.35

Figure 7. System Schematic for  $N_2H_4$  Catalytic- $N_2H_4$  Resistojet

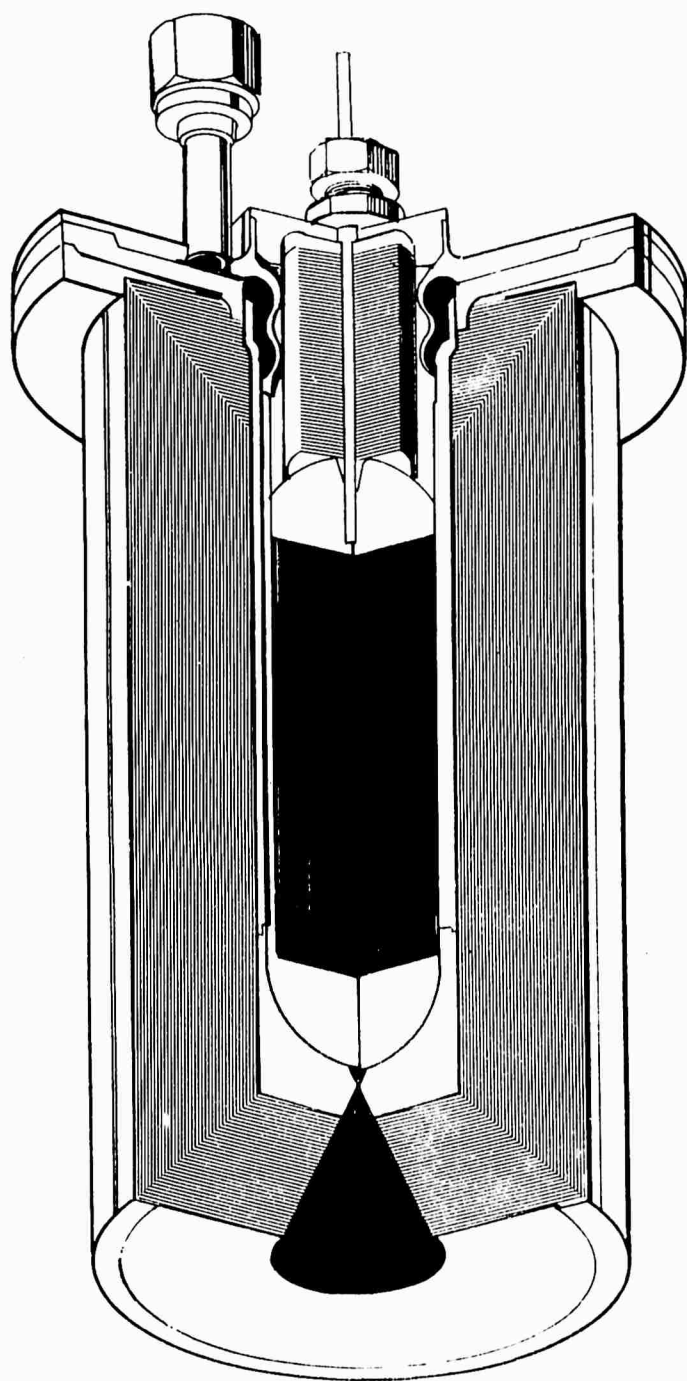


Figure 8.  $\text{N}_2\text{H}_4$  Radioisotope Thruster

a. 5-lb<sub>f</sub> Thruster

The large hydrazine catalytic thruster is identical to that described in Section III. B. 1.

b. 0.025-lb<sub>f</sub> Thruster

For a thrust level of 25 millipounds, a minimum impulse bit of  $5 \times 10^{-4}$  lb<sub>f</sub>-sec was used for limit cycling. Pulse mode specific impulse was taken to be 250 seconds on the basis of a capsule temperature of 2000°F. (Steady-state Isp is 220 seconds.) A vented capsule will be required to achieve the 10-year life requirement.

c. Conceptual Schematic

Figure 9 shows the conceptual schematic.

6. N<sub>2</sub>H<sub>4</sub> Catalytic/DART

The decomposed ammonia radioisotope thruster (DART) has been under AFRPL-sponsored development with TRW since 1965 (AF04(611)-11536). A DART prototype thruster was demonstrated at the AEC Mound Laboratory in January 1967. An advanced DART prototype has been designed by the Los Alamos Scientific Laboratories and is presently undergoing evaluation. Since 1969, DART has been a part of the SAMSO ADP for Advanced Satellite Propulsion, and a current \$50,000 study is concerned with problems associated with spacecraft integration.

a. 5-lb<sub>f</sub> Thruster

The large hydrazine catalytic thruster is identical to that described in Section III. B. 1.

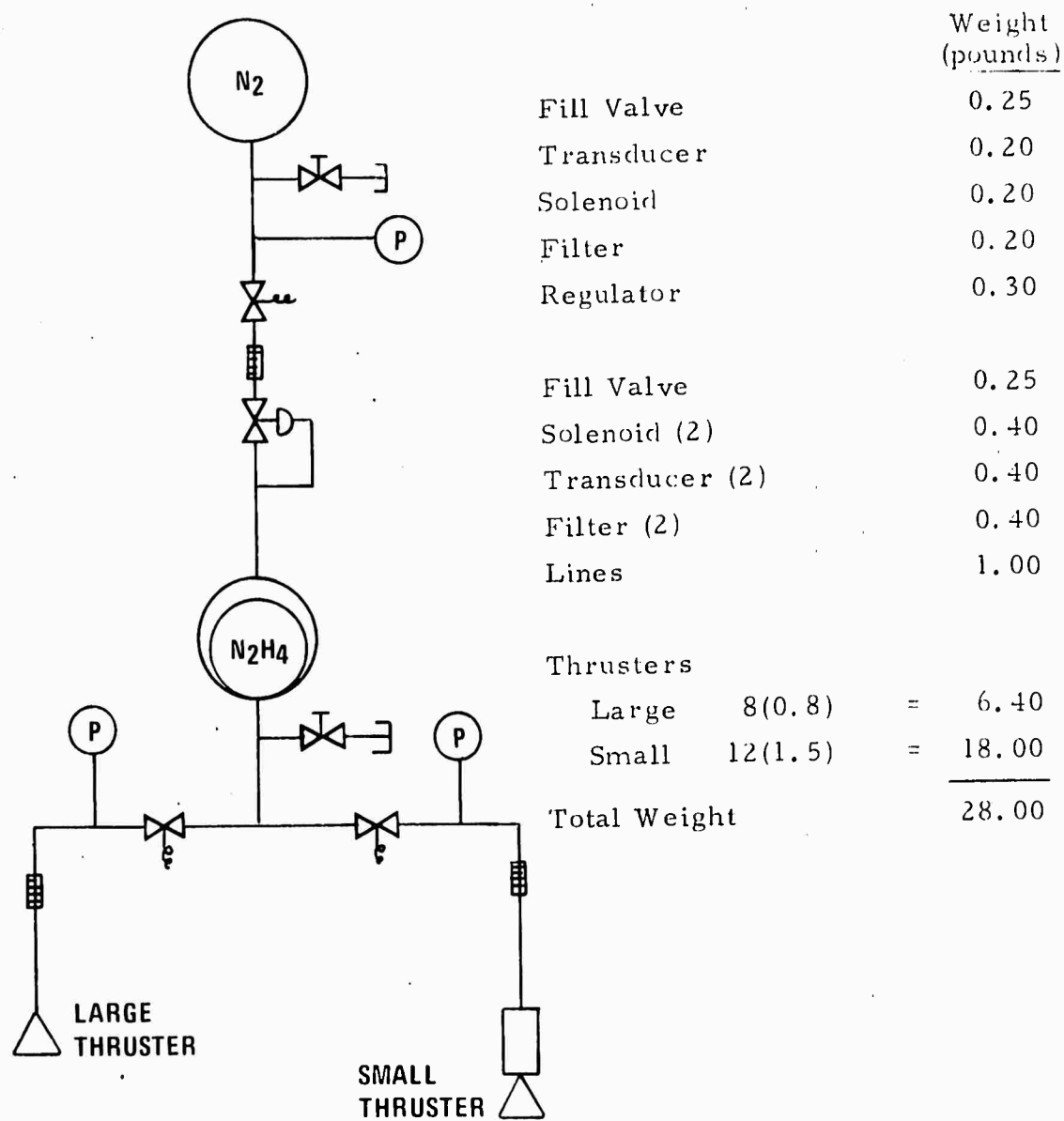


Figure 9. System Schematic for  $N_2H_4$  Catalytic- $N_2H_4$  Radioisotope

b. 0.025-lb<sub>f</sub> Thruster

Performance for DART was based upon a capsule temperature of 2500° F. For a thrust level of 25 millipounds, a minimum impulse bit of  $5 \times 10^{-4}$  lb<sub>f</sub>-sec was used for this study. Specific impulse numbers are 310 seconds pulsed, and 280 seconds at steady-state.

c. Design and Conceptual Schematic

Figure 10 shows the thruster design and Figure 11 is the conceptual schematic.

7. N<sub>2</sub>H<sub>4</sub> Catalytic/Cesium Bombardment Ion

The electron bombardment engine uses an anode-cathode arrangement to ionize a propellant such as mercury or cesium. The ions are accelerated in an electrostatic field and neutralized as they are emitted to avoid the limitations of space charge flow (Figure 12). While the ionization potential for cesium is less than that of mercury, the cross section for electron-atom interactions for mercury is greater than for cesium. The result is that both propellants are equally easy to ionize.

NASA/Lewis Research Center mercury bombardment thrusters (Kaufman thrusters) have flown on SERT-I and SERT-II satellites. An Electrical Optical Systems (EOS) cesium bombardment ion engine has been tested as an experiment aboard an Air Force satellite. Cesium is easily handled by passive zero-g feed systems (Figure 13) and has a high mass utilization efficiency as long as the cesium is kept above its freezing point. Due to long start and shutdown transients, high-frequency pulsing is not practical for the ion engine. Also, power requirements are extremely sensitive to thrust and range from 15 watts at 10 μ-lb<sub>f</sub> to 1300 watts at 10 mlb<sub>f</sub> thrust.

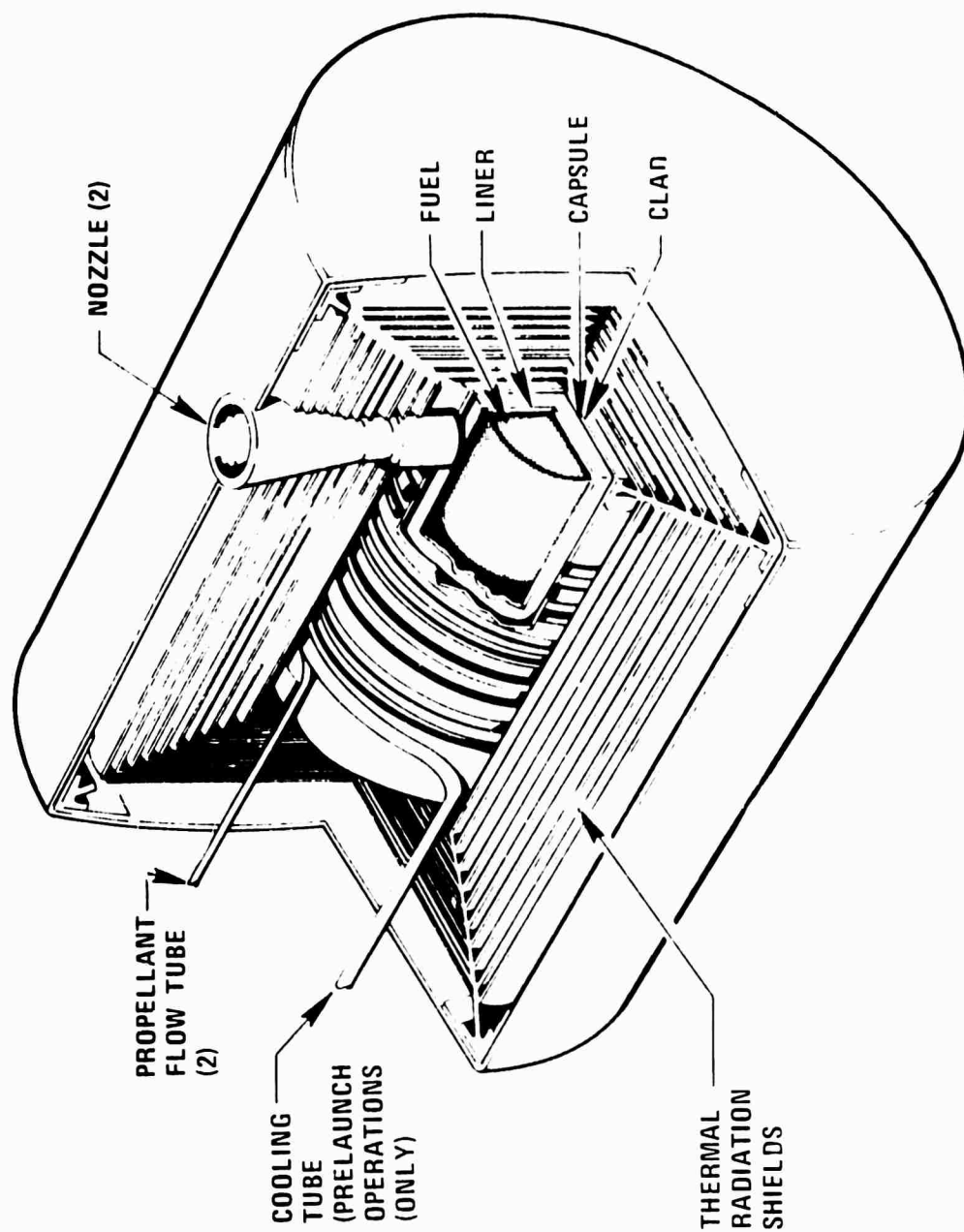


Figure 10. DART Thruster



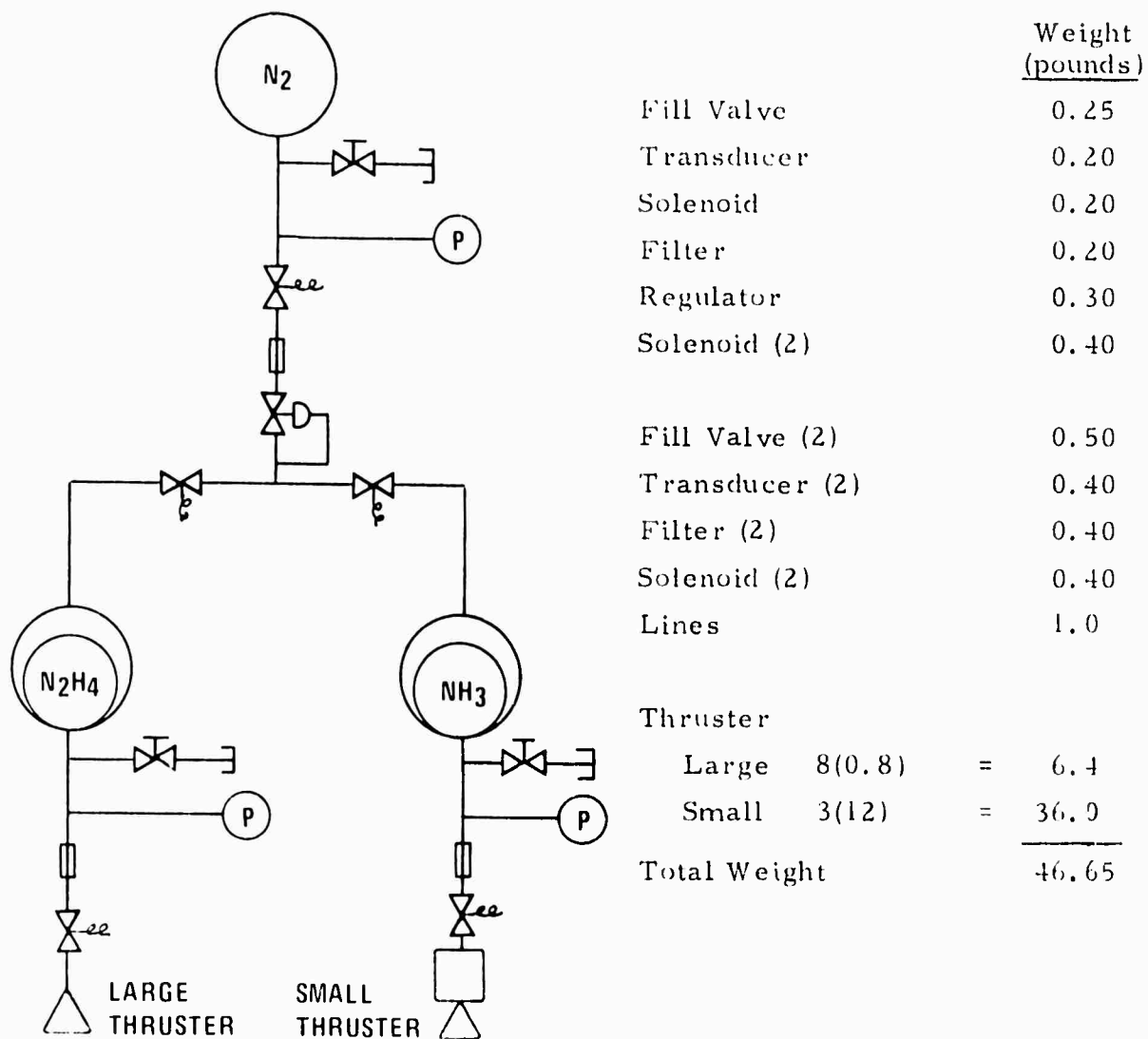


Figure 11. System Schematic for  $N_2H_4$  Catalytic-DART

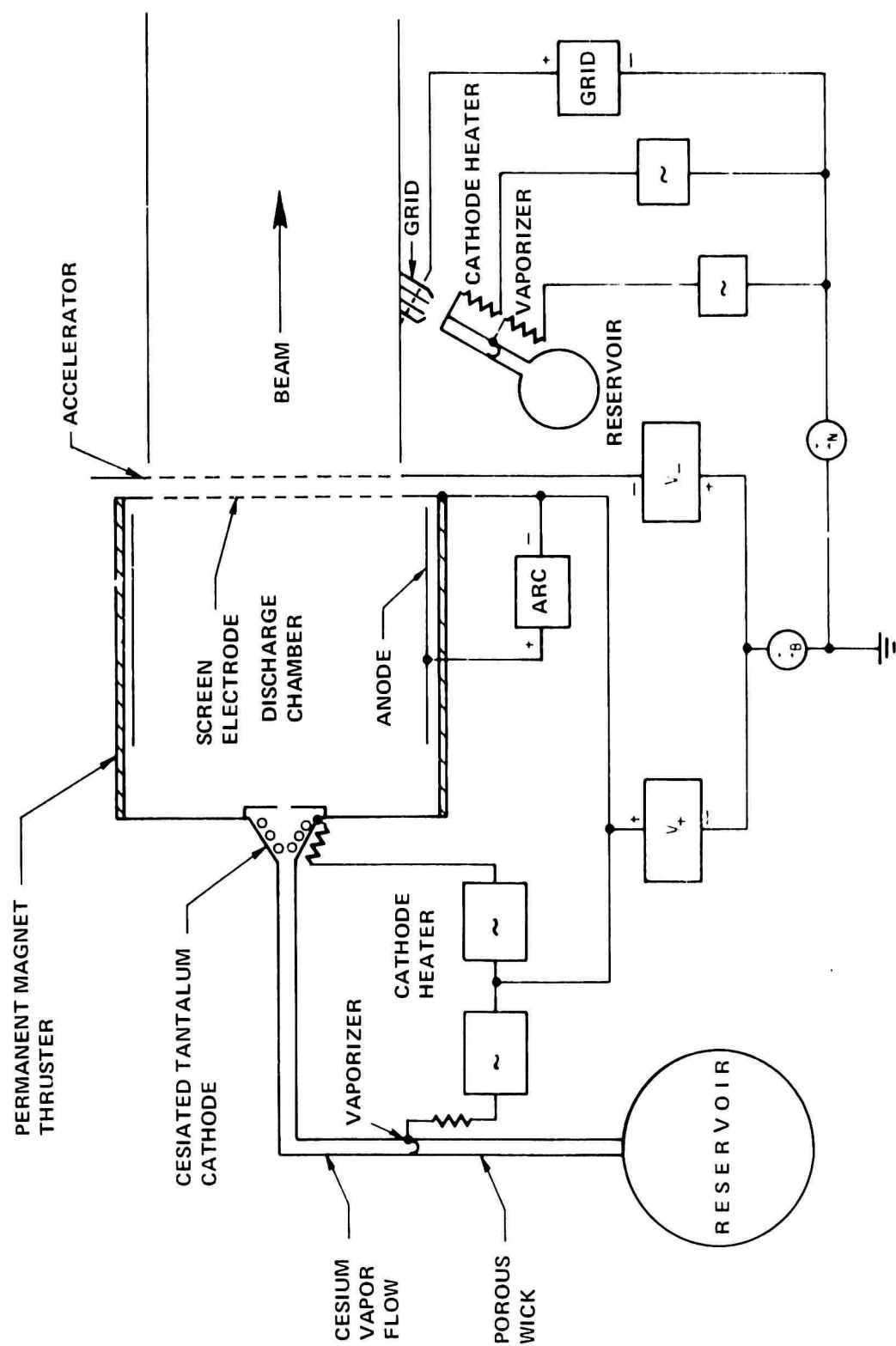


Figure 12. Cesium Ion Engine Schematic

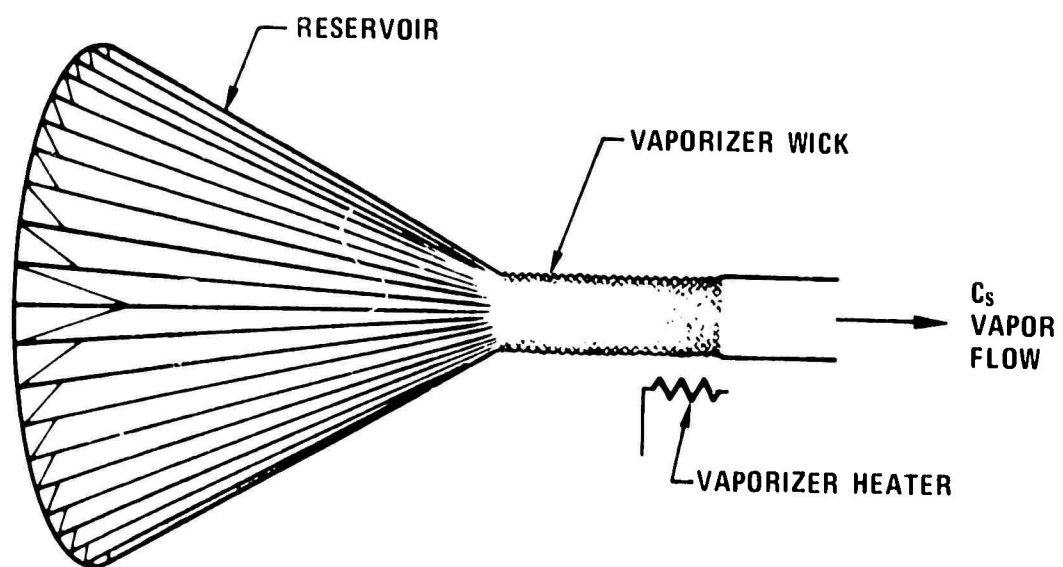


Figure 13. Cesium Feed System

a. 5-lb<sub>f</sub> Thruster

The large hydrazine catalytic thruster is identical to that described in Section III. B. 1.

b. 0.001-lb<sub>f</sub> Thruster

The 1-millipound thrust size for the low-level thruster was chosen to keep the power requirements around 150 watts. Although EOS life-tested two 8-millipound bombardment ion thrusters, their power consumption was on the order of 1 kilowatt. For a 1-millipound thruster and 150 watts power, a specific impulse of 3000 seconds is projected. A minimum impulse bit of  $1 \times 10^{-3}$  lb<sub>f</sub>-sec was considered reasonable, based on a 1-second minimum pulse width. (The above performance goals were obtained from Dr. Fritz, AFAPL/POP-2 of the Air Force Aero Propulsion Laboratory.)

c. Conceptual Schematic

Figure 14 shows the conceptual schematic.

8. N<sub>2</sub>H<sub>4</sub> Catalytic/Colloid

The basis for the colloid engine (Figures 15 and 16) is an electrically conducting propellant subjected to a high electric field established between the propellant and an extractor electrode. The extractor electrode has historically been a small-diameter (4-mil bore) capillary needle, but recent development effort has been expended on a linear slit geometry electrode version. Once the electrode field is established, field emission ionization of small-diameter ( $100 \text{ \AA}$ ) droplets occurs at the needle tip or linear slit. The same field which produces ionization also accelerates the charged droplets to produce thrust. Since the charged droplets may be positive or negative depending on the polarity of the potential applied to

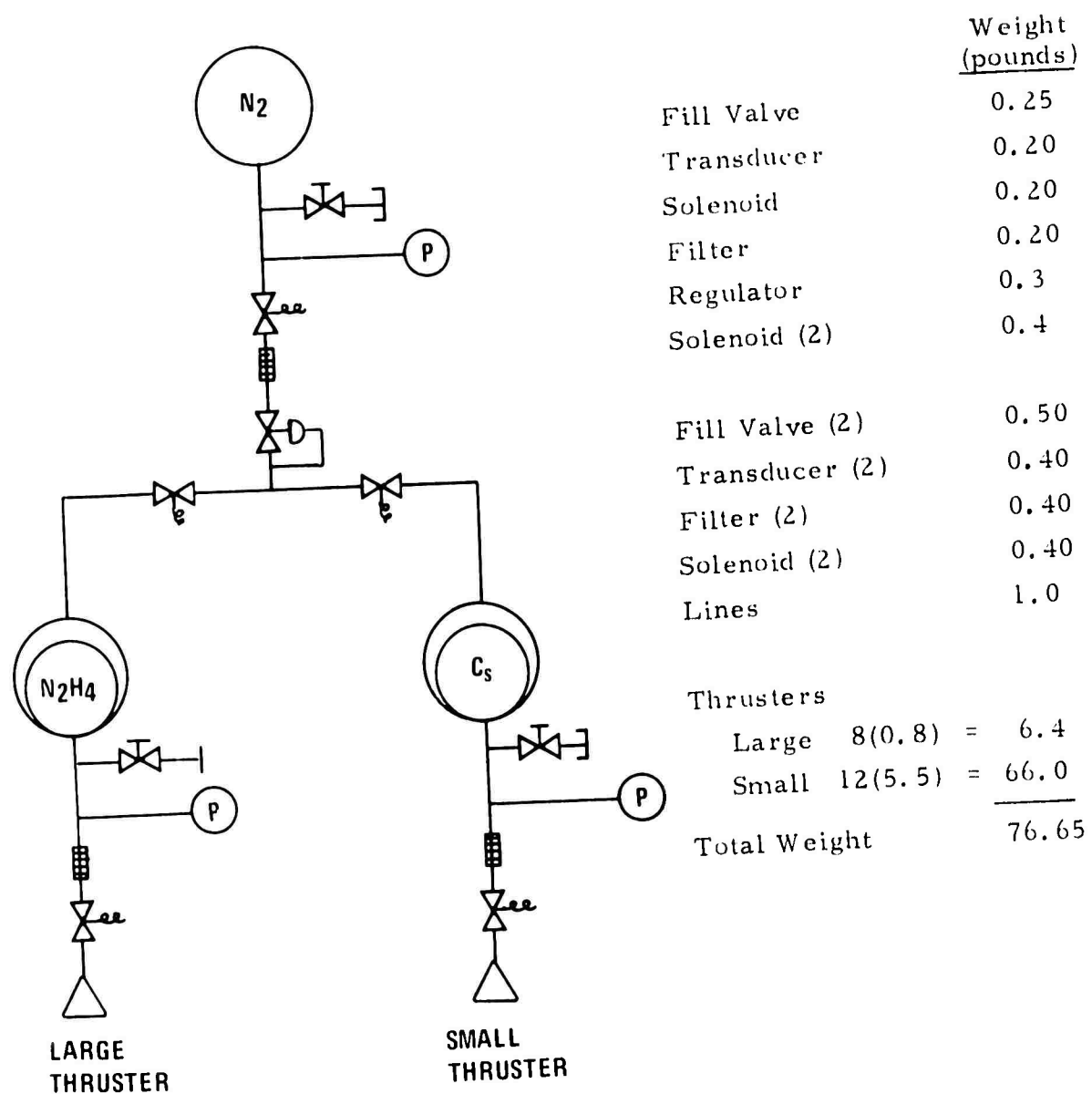


Figure 14. System Schematic for  $N_2H_4$  Catalytic-Cs Ion

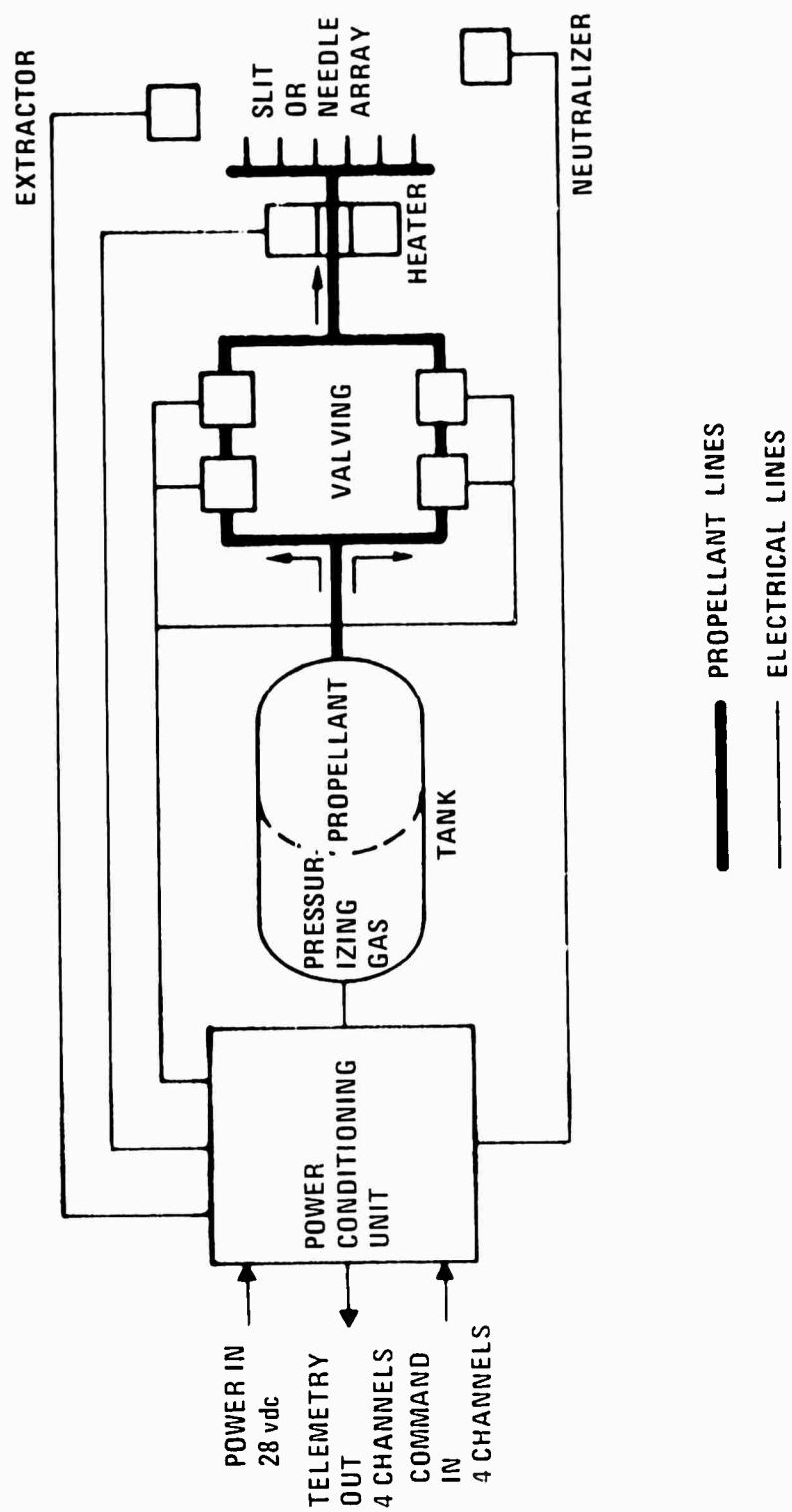


Figure 15. Colloid Engine Schematic

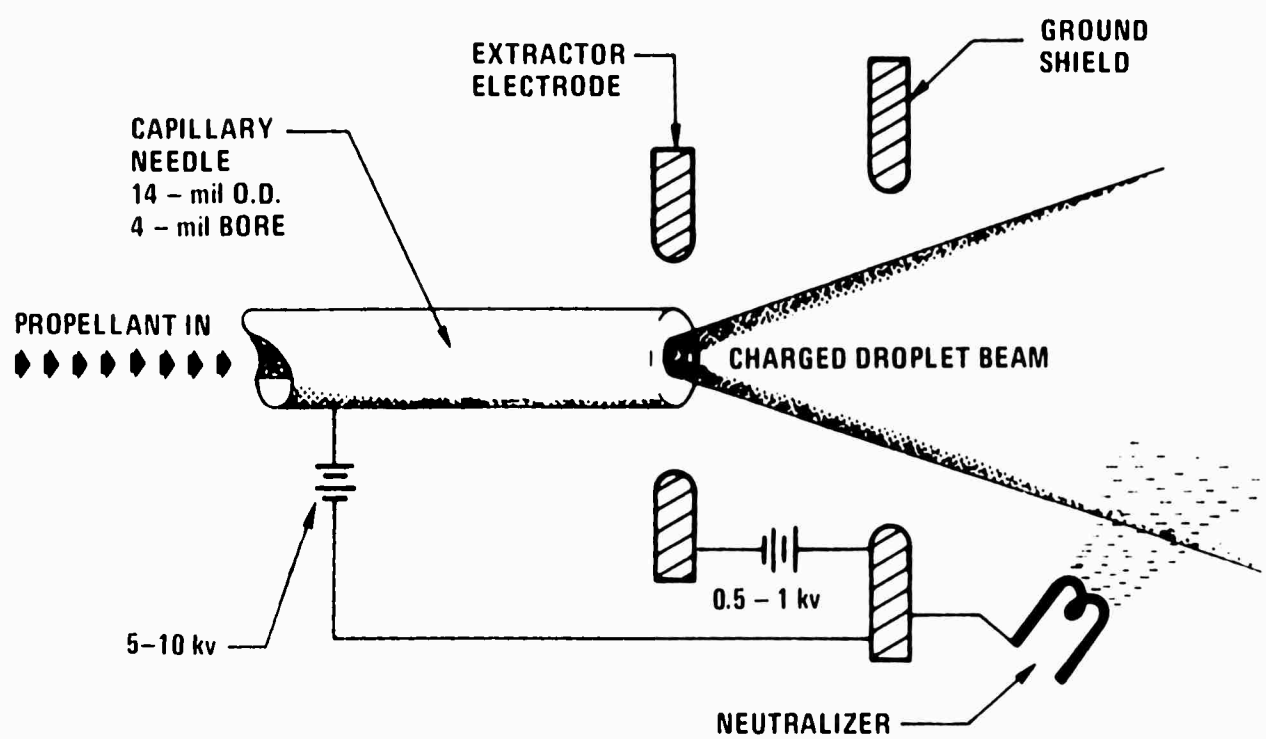


Figure 16. Colloid Thruster Concept

the needles, a neutralizer is necessary to neutralize the beam. The masses of the charged droplets are generally greater than the masses of ions produced in ion engines.

Although the colloid engine is degraded by the randomness of the particle formation and the manner of inducing the charge, it alone, of the electrostatic engines, has the most efficient formation of charged particles.

The most successful colloid engine work has been performed by TRW Systems for the Air Force Aero Propulsion Laboratory (AFAPL). TRW built a Colloid Microthruster Experiment (CME) for the AFAPL in support of the DODGE-II satellite, which was cancelled. The CME flight hardware was subsequently tested for 1000 hours during 1969.

Since 1969, the TRW colloid thruster has been part of the SAMSO ADP for Advanced Satellite Propulsion. In December 1970, TRW was awarded a 56-month contract by SAMSO for development of a 1-millipound-thrust colloid thruster. The thruster, resembling a 10-inch cube with 12 individual thrusting modules, will weigh about 20 pounds and carry some 25 pounds of propellant, mainly glycerol with sodium iodide. At the 1-millipound thrust level, the colloid engine will have a specific impulse of 1500 seconds and deliver about 35,000  $\text{lb}_f\text{-sec}$  of total impulse. The contract calls for ground testing of three flight qualified thrusters for 10,000 hours and delivery of three systems for satellite flight testing to provide satellite stationkeeping for 7 years.

a. 5- $\text{lb}_f$  Thruster

The large hydrazine catalytic thruster is identical to that described in Section III.B.1.

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\*Space Business Daily, 2 December 1970



b. 0.001-lb<sub>f</sub> Thruster

The current SAMSO ADP for colloid propulsion was used to obtain propulsion system characteristics. For this study, thrust level was 1 millipound, Isp was 1500 seconds and minimum impulse bit was  $1 \times 10^{-4}$  lb<sub>f</sub>-sec. The propellant is 20 percent NaI and 80 percent glycerol (percent by weight).

A lightweight and reliable feed system remains the largest development effort. No pulse tests have been performed on the linear slit to date. The needle has been pulsed between 1 and 3 pulses/sec in duty cycles of 10 and 30 percent. Although the low power required (70 watts) for the colloid thruster is favorable, the linear slit requires between 14 and 16 kilovolts for operation and is the weak point in the system.

c. Conceptual Schematic

Figure 17 shows the conceptual schematic.

9. N<sub>2</sub>H<sub>4</sub> Catalytic/Hg Pulsed Plasma

Although several types of pulsed plasma thrusters have been undergoing exploratory development (Figure 18), only the pulsed vacuum arc thruster (Figure 19) being developed by Cornell Aeronautical Laboratories uses a liquid propellant (mercury) which permits this system to achieve a total impulse level required for a SYNCSAT (USAF Contract No. F33615-67-C-1579, Report AFAPL-TR-68-92). The general mode of operation is for mercury to be ionized by a high-voltage discharge and accelerated by the interaction of the discharge current with its own magnetic field. The PVAT produces only discrete impulses, the effective "thrust" being governed by the size of these impulse bits and the repetition rate. Typical impulse-per-pulse figures range from  $10^{-6}$  to  $10^{-5}$  lb<sub>f</sub>-sec while repetition rates from zero to 50 pulses/sec are readily attainable.

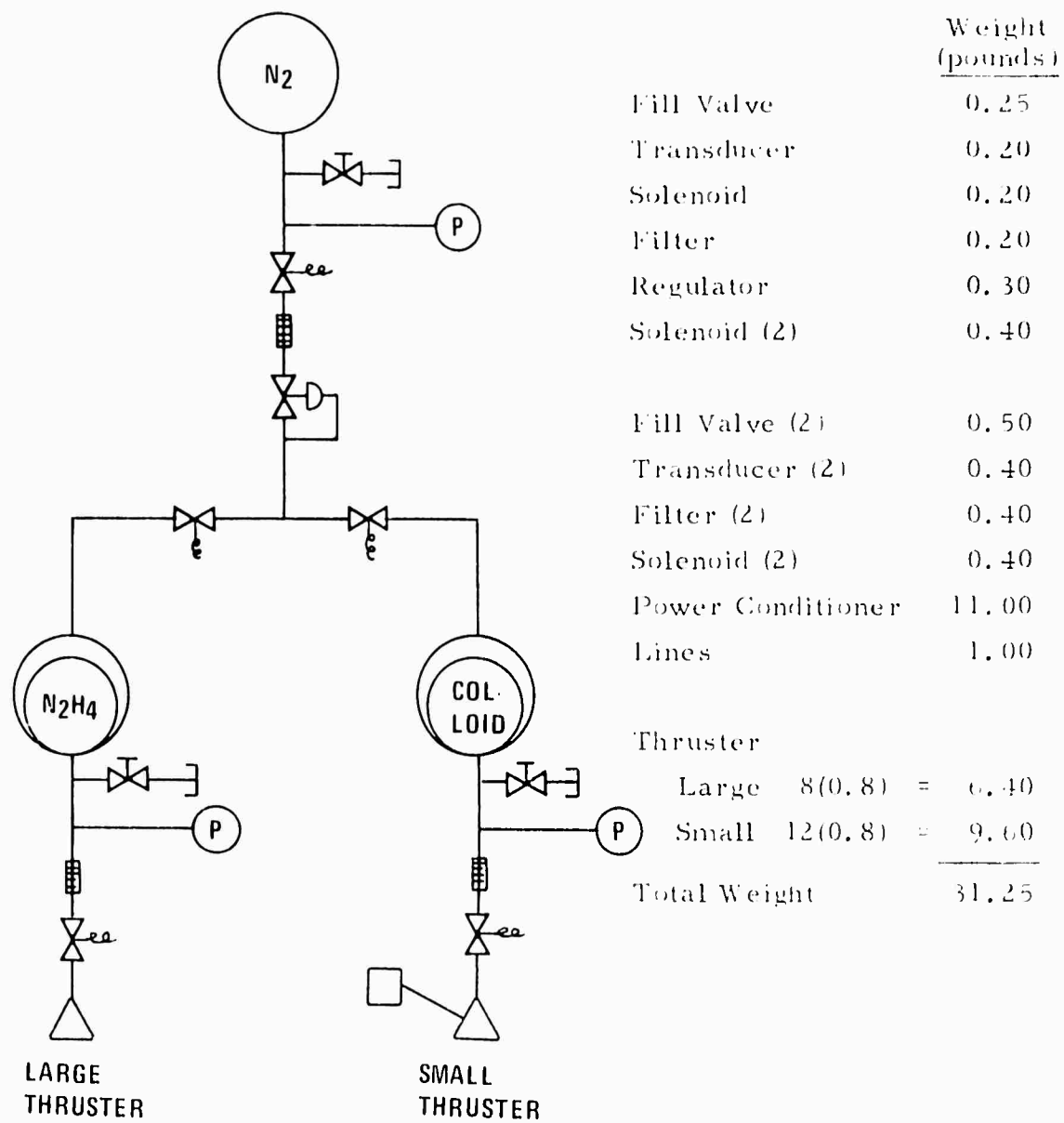


Figure 17. System Schematic for  $N_2H_4$  Catalytic-Colloid

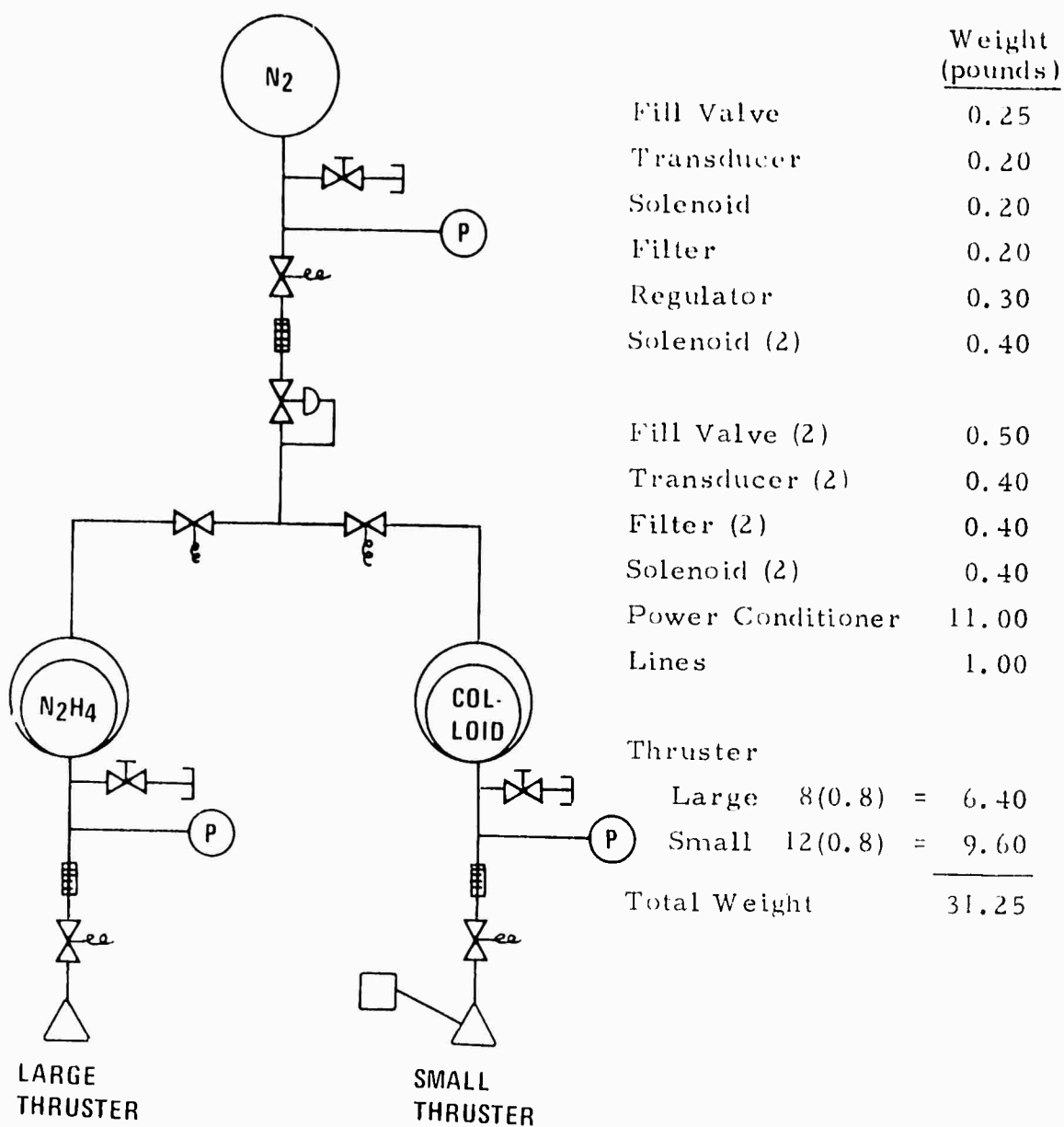


Figure 17. System Schematic for  $N_2H_4$  Catalytic-Colloid

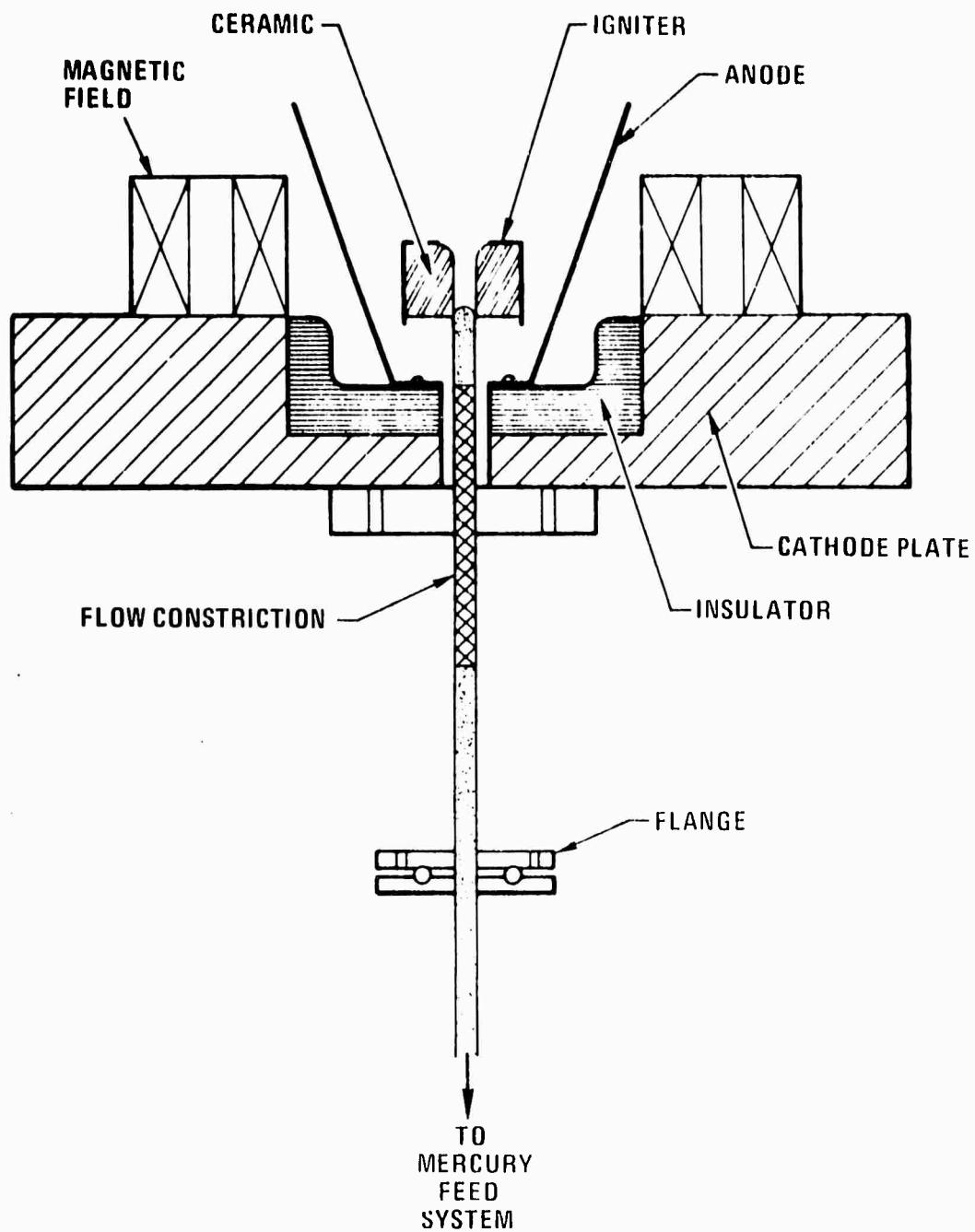


Figure 19. Pulsed Vacuum Arc Thruster

Lifetimes up to  $6 \times 10^7$  pulses have been demonstrated on several pulsed vacuum arc thrusters (PVATs). To date, the mercury-cathode PVAT, however, has been run for only about  $4 \times 10^5$  pulses because of feed system problems.

a. 5-lb<sub>f</sub> Thruster

Performance for the  $N_2H_4$  thruster was  $I_{sp} = 230$  seconds steady-state vacuum. All members are identical to those previously used in Section III. B. 1.

b. 0.00001-lb<sub>f</sub> Thruster

Data used in this study were based on the PVAT being developed by Cornell Aeronautical Laboratories. This study used a thrust level of 10 micropounds force, a specific impulse of 1500 seconds and a minimum impulse bit of  $5 \times 10^{-6}$  lb<sub>f</sub>-sec.

The PVAT still needs considerable development in the feed system area and more life testing of an integrated system. For the SYNCSAT, power requirements are on the order of 100 watts for each PVAT.

c. Conceptual Schematic

Figure 20 shows the conceptual schematic.

10. DO Radioisotope/DO Radioisotope

DO (dioxyamine) is a new type of monopropellant presently being characterized by the AFRPL. Because of the high (2600°F) equilibrium flame temperature of DO, it is difficult to project the early development of a catalyst and substrate to decompose DO. For this reason, a radioisotope capsule is envisioned as the ignition scheme to initiate thermal decomposition for the purposes of this study.

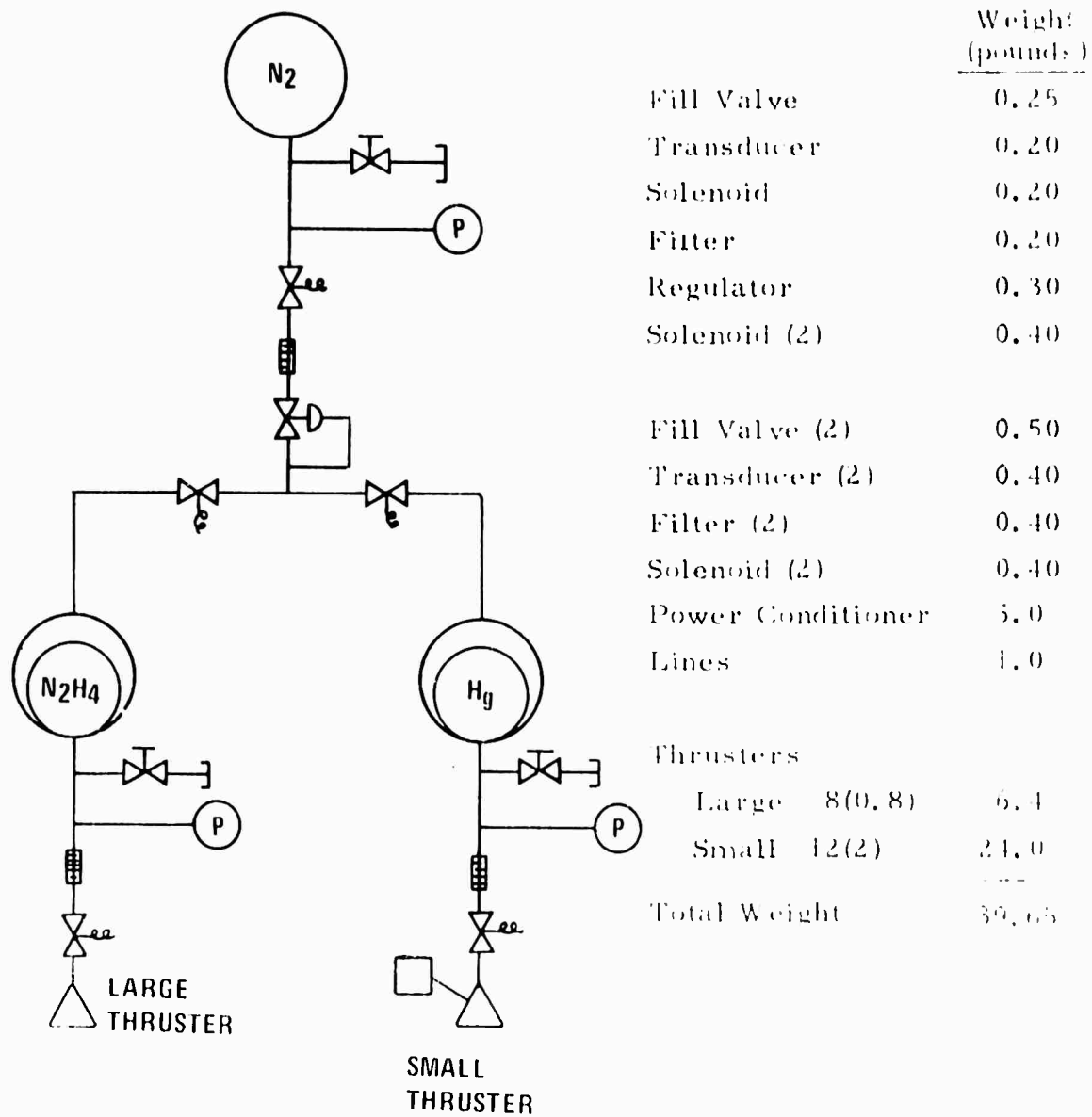


Figure 20. System Schematic for  $N_2H_4$  Catalytic-Hg Pulsed Plasma

The AFRPL performance calculation computer code (ODIE) was used to calculate a theoretical altitude performance number for DO using a combustion chamber pressure of 100 psia, a nozzle expansion ratio of 40 and a 55 percent  $\text{NH}_3$  dissociation. These inputs gave a theoretical steady-state altitude specific impulse of 283 seconds. Using a 94 percent efficiency factor, a realizable specific impulse of 265 seconds might be obtained.

a. 5-lb<sub>f</sub> Thruster

Steady-state performance for the 5-pound DO thruster was taken as 265 seconds, as mentioned above. This number is based on 94 percent engine efficiency and is a "best" estimate. No engine data are available.

b. 0.025-lb<sub>f</sub> Thruster

For the 25-millipound thruster, a minimum impulse bit of  $5 \times 10^{-4}$  lb<sub>f</sub>-sec was assumed, based on the DART ADP goals. Pulse mode performance is  $I_{sp} = 238$  seconds based on a capsule temperature of 2500 °F. No test data are available.

c. Conceptual Schematic

Figure 21 shows the conceptual schematic.

## II. DO Radioisotope/Colloid

This is a hybrid propulsion system comprised of two previously described units. A radioisotope thermal decomposition ignition system is postulated for the 5-lb<sub>f</sub> DO thruster. The colloid thruster is of 1-millipound thrust with performance numbers as described in the SAMSO ADP for the NaI plus glycerol colloid propulsion development effort.

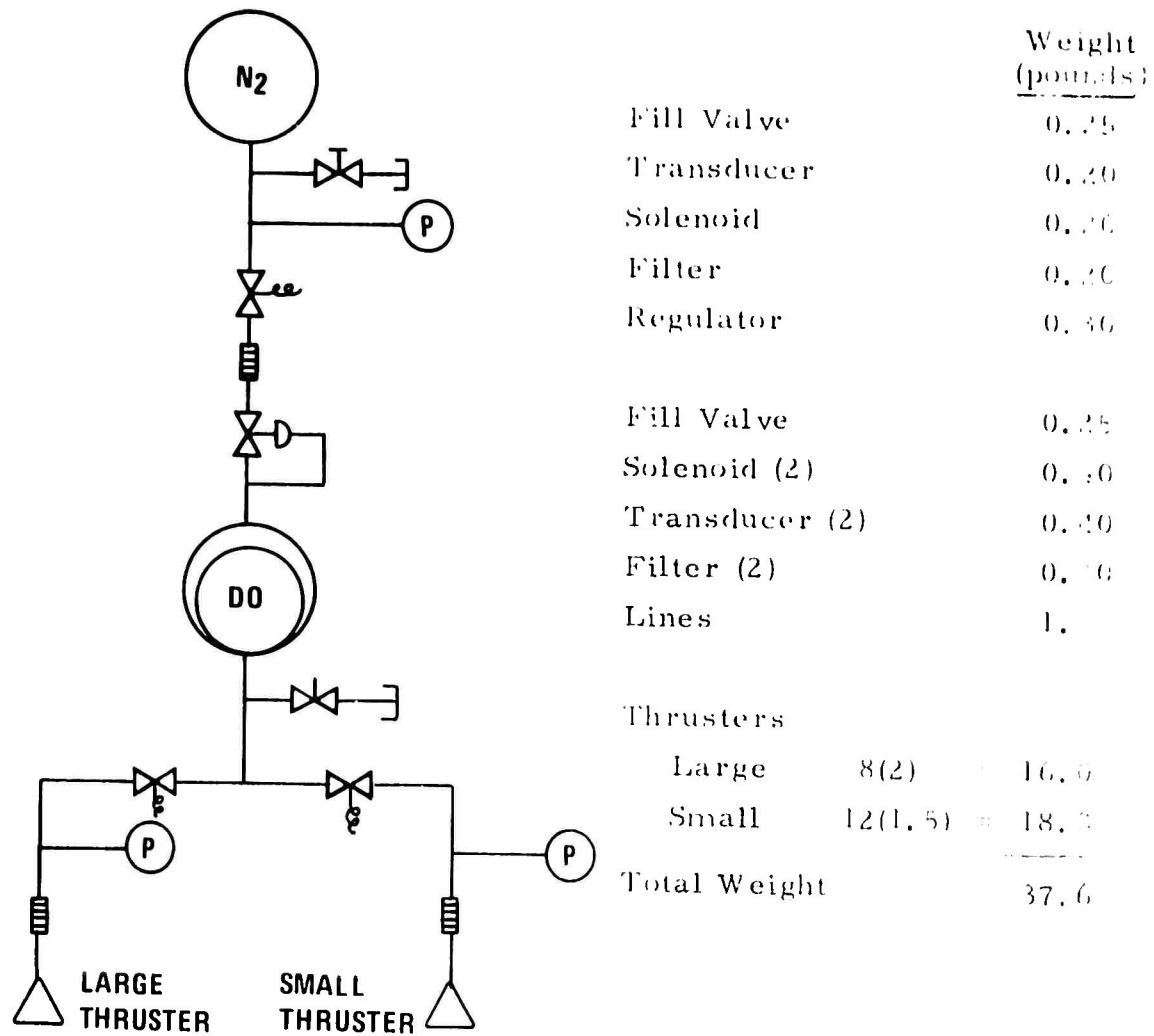


Figure 21. System Schematic for DO-DO



a. 5-lb<sub>f</sub> Thruster

The large DO radioisotope thruster is identical to that described in Section III. B. 10.

b. 0.001-lb<sub>f</sub> Thruster

The small colloid thruster is identical to that described in Section III. B. 8.

c. System Schematic

Figure 22 shows the system schematic.

12. H<sub>2</sub>O Electrolysis/H<sub>2</sub>O Electrolysis

The water electrolysis propulsion system employs liquid water as the propellant in the storage mode and gaseous hydrogen and oxygen for the bipropellant rocket thrusters. A zero-g water electrolysis unit provides the separated gases for the engine. This scheme permits storing liquid water at low pressure and reduces the total system weight in this manner. A recent AFRPL contract (F04611-71-C-0055) to the Marquardt Corporation provides for the development and testing of a bipropellant 5-lb<sub>f</sub> thruster and a bipropellant 0.1-lb<sub>f</sub> thruster using gaseous hydrogen and oxygen. General Electric is the subcontractor for the zero-g water electrolysis unit. Twenty watts of continuous power are required.

a. 5-lb<sub>f</sub> Thruster

Steady-state performance for the large 5-lb<sub>f</sub> GH<sub>2</sub>/GO<sub>2</sub> engine (Figure 23) was based on Marquardt prototype test data. This number is 1sp - 350 seconds with a thrust coefficient equal to 1.6. A pulsing performance of 1sp - 310 seconds was assumed for this thruster. GH<sub>2</sub>/GO<sub>2</sub> thrusters provide high performance and highly reproducible pulses.

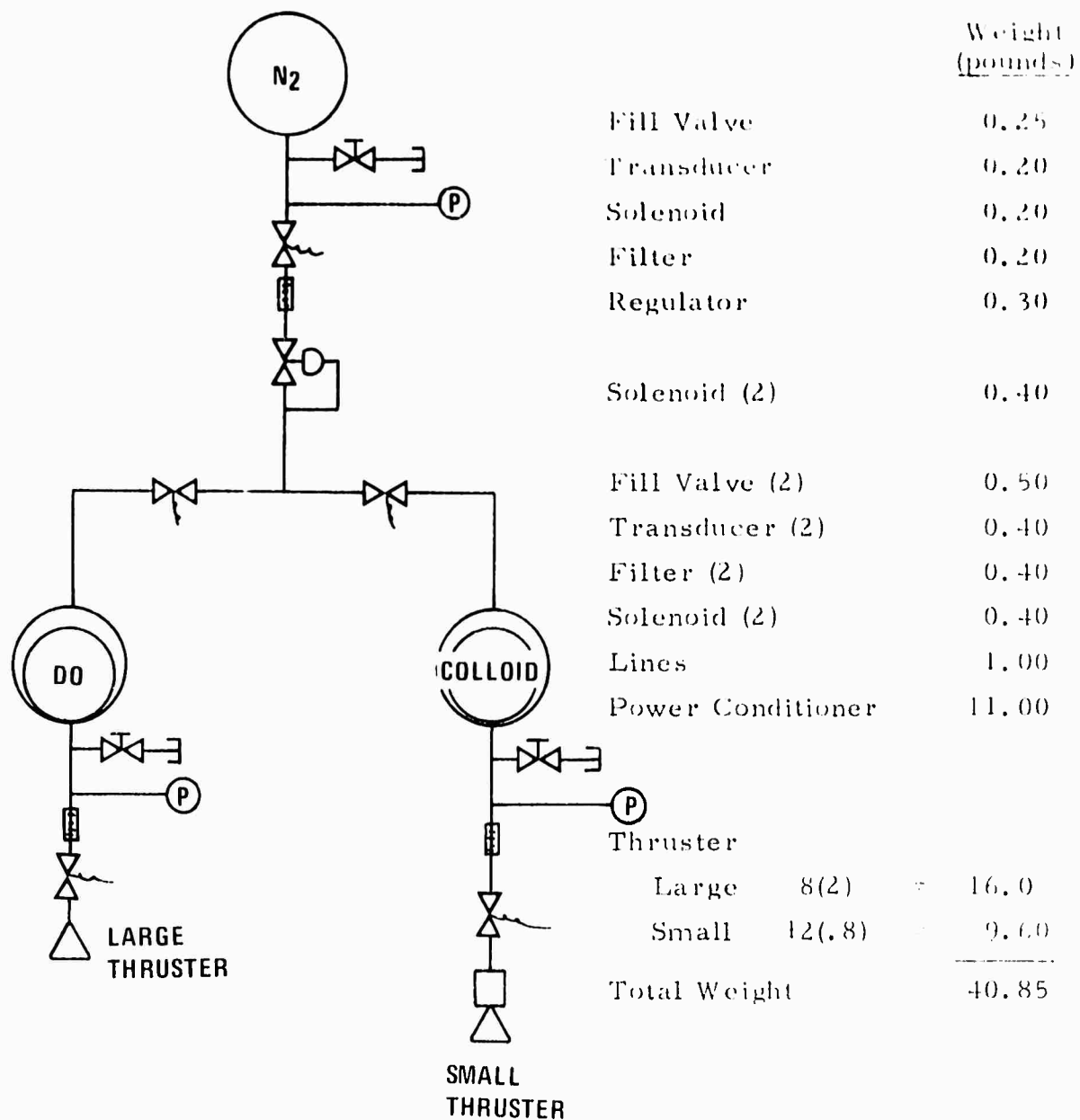


Figure 22. System Schematic for DO-Colloid

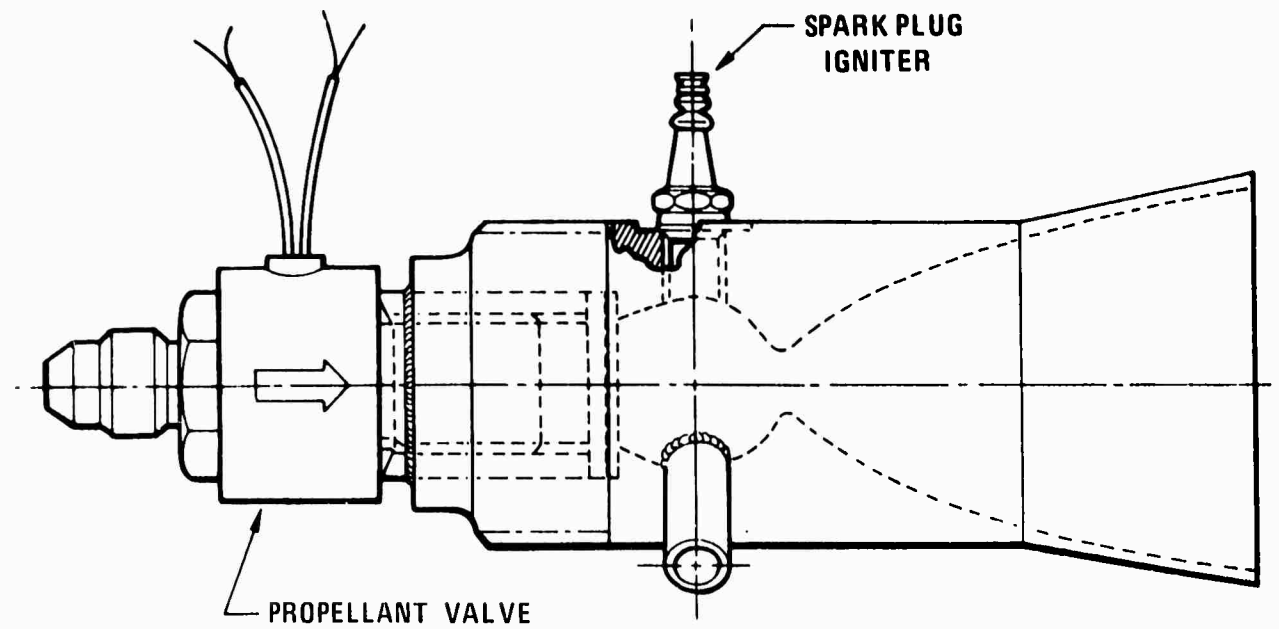


Figure 23. Water Electrolysis Bipropellant Thruster

b. 0.1-lb<sub>f</sub> Thruster

The small thruster pulse mode Isp was assumed to be 280 seconds. Using a 25-millisecond pulse width, a minimum impulse bit of  $2.5 \times 10^{-3}$  lb<sub>f</sub>-sec was taken. Steady-state performance for the 0.1-lb<sub>f</sub> thruster was assumed to be Isp = 310 seconds.

In general, this system lacks feed system and integration testing. System weight reduction is at the expense of system complexity. A high system reliability must be demonstrated early in its development.

c. Conceptual Schematic

Figure 24 shows the conceptual schematic.

13. H<sub>2</sub>O Electrolysis/Colloid

This hybrid propulsion system is designed to provide a high-performance chemical rocket engine with electrical colloid thruster. Both units have been described previously.

a. 5-lb<sub>f</sub> Thruster

The large GH<sub>2</sub>/GO<sub>2</sub> bipropellant thruster is identical to the water electrolysis system described in Section III. B. 12.

b. 0.001-lb<sub>f</sub> Thruster

The small colloid thruster is identical to that described in Section III. B. 8.

c. Conceptual Schematic

The conceptual schematic is shown in Figure 25.

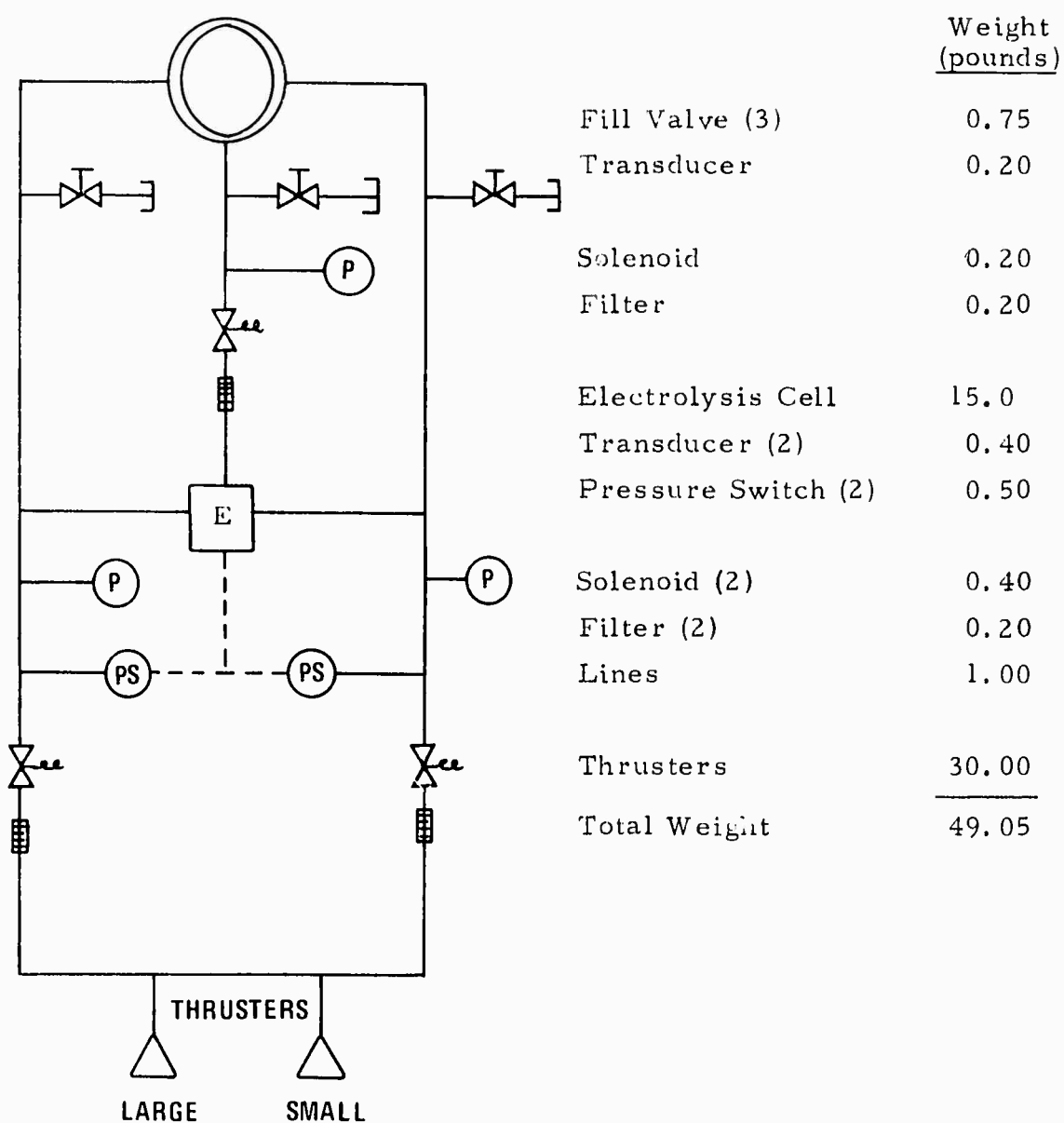


Figure 24. System Schematic for  $H_2O-H_2O$

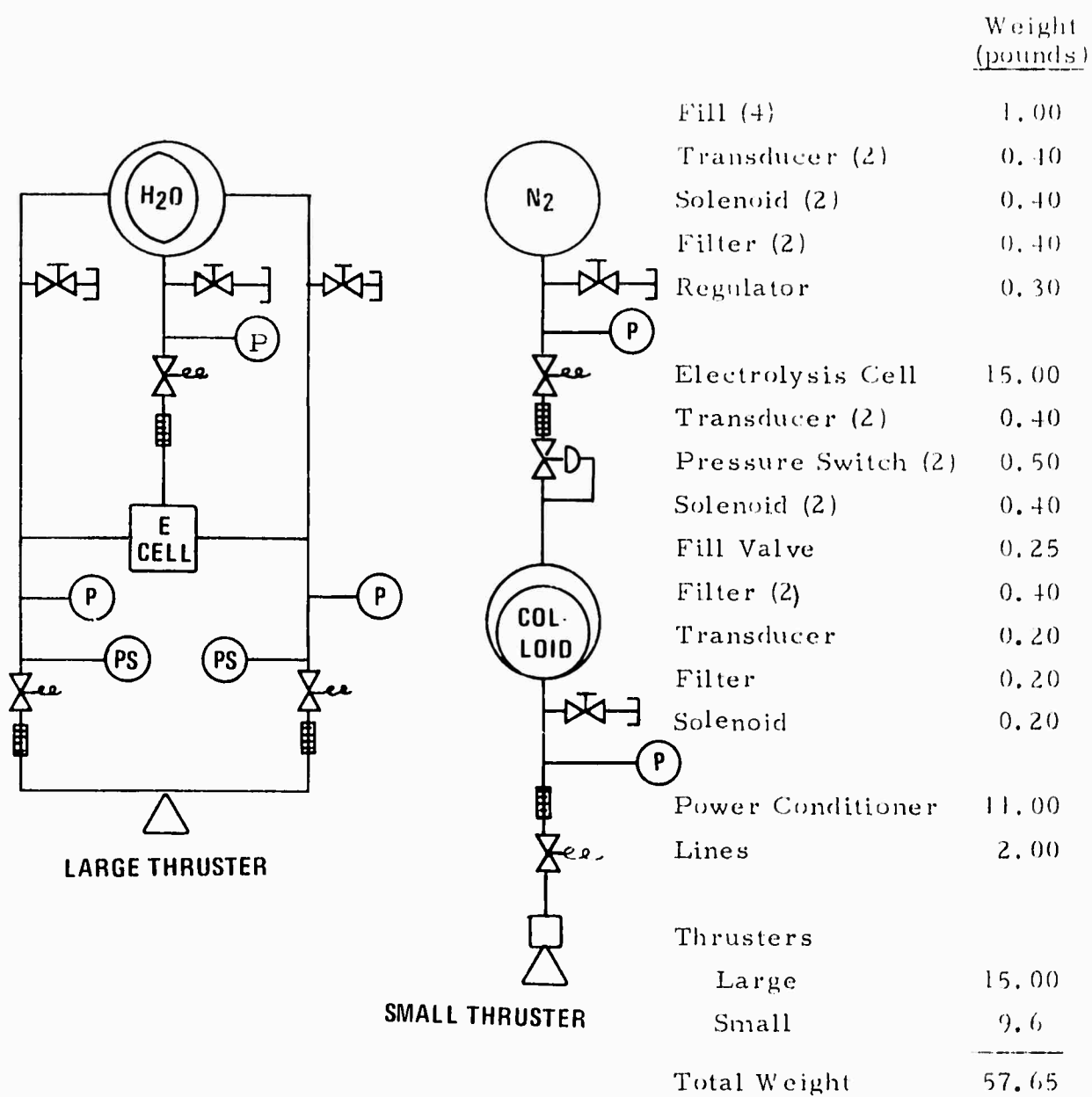


Figure 25. System Schematic for H<sub>2</sub>O-Colloid

#### 14. $\text{N}_2\text{O}_4/\text{N}_2\text{H}_4$ Bipropellant/ $\text{N}_2\text{H}_4$ GG Plenum

Although a 5-lb<sub>f</sub> bipropellant thruster using  $\text{N}_2\text{O}_4$  and hydrazine has not yet been developed, a large number of 5-lb<sub>f</sub> engines using  $\text{N}_2\text{O}_4$ /MMH and  $\text{N}_2\text{O}_4$ /50 percent  $\text{N}_2\text{H}_4$ -50 percent UDMH have been built and tested. This system is designed to use the common hydrazine tank for both the high and low thrusters, thereby providing for simplicity and weight reduction. The earth storable bipropellants are well defined in terms of properties and characteristics. The only required power is that needed to operate the propellant valves.

##### a. 5-lb<sub>f</sub> Thruster

Since no 5-lb<sub>f</sub> thrust  $\text{N}_2\text{O}_4/\text{N}_2\text{H}_4$  test data were available, steady-state 5-lb<sub>f</sub> thruster performance numbers for  $\text{N}_2\text{O}_4$ /MMH were used. This yielded steady-state operation at  $I_{sp} = 280$  seconds for an area ratio of 40:1 at a mixture ratio of 1.40.

##### b. 0.050-lb<sub>f</sub> Thruster

The low-thrust hydrazine gas generator plenum system was capable of giving  $I_{sp} = 110$  seconds and a minimum impulse bit of  $5 \times 10^{-4}$  lb<sub>f</sub>-sec. These numbers are identical to the hydrazine plenum system described in Section III.B.2.

##### c. Conceptual Schematic

Figure 26 shows the conceptual schematic.

#### 15. $\text{ClF}_5/\text{N}_2\text{H}_4$ Bipropellant/ $\text{N}_2\text{H}_4$ GG Plenum

This bipropellant system is similar to the  $\text{N}_2\text{O}_4$  system described in Section III.B.14, except that care must be exercised in the selection of a  $\text{ClF}_5$  storage tank. A tank material compatibility problem exists which

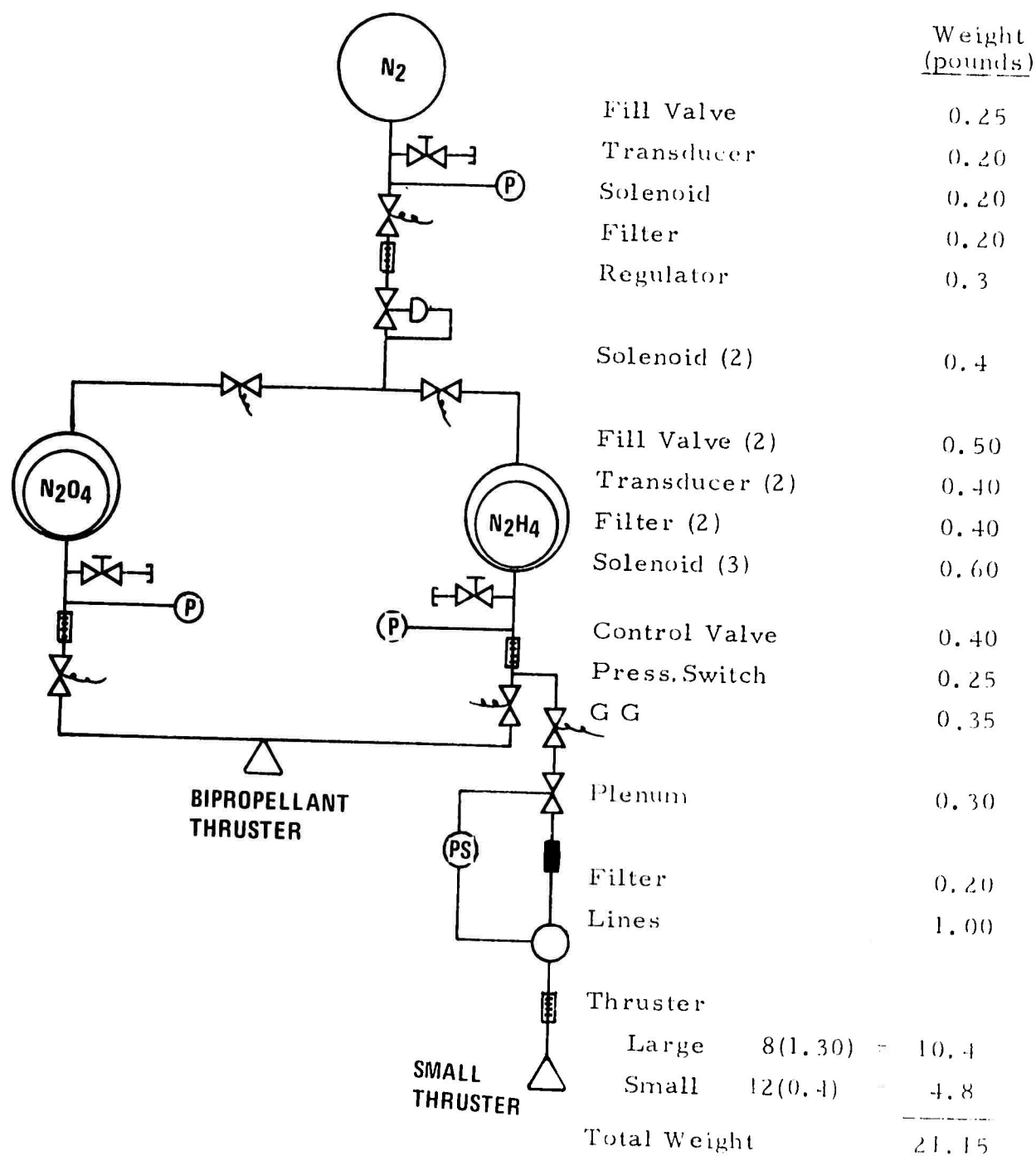


Figure 26. System Schematic for  $N_2O_4/N_2H_4-N_2H_4$  GG Plenum



was not experienced with  $\text{N}_2\text{O}_4$ . No performance data for a 5-lb<sub>f</sub>  $\text{ClF}_5/\text{N}_2\text{H}_4$  thruster are available. The only required power is that needed to operate the propellant valves.

a. 5-lb<sub>f</sub> Thruster

For this study, a 10-second specific impulse gain above the  $\text{N}_2\text{O}_4/\text{N}_2\text{H}_4$  system was assumed. Therefore, steady-state performance was  $I_{sp} = 290$  seconds at a mixture ratio of 2.0.

b. 0.050-lb<sub>f</sub> Thruster

Once again, the hydrazine gas generator plenum performance numbers were identical to those used previously in Section III. B. 2.

c. Conceptual Schematic

Figure 27 shows the conceptual schematic.

16. ADP DART/ADP DART

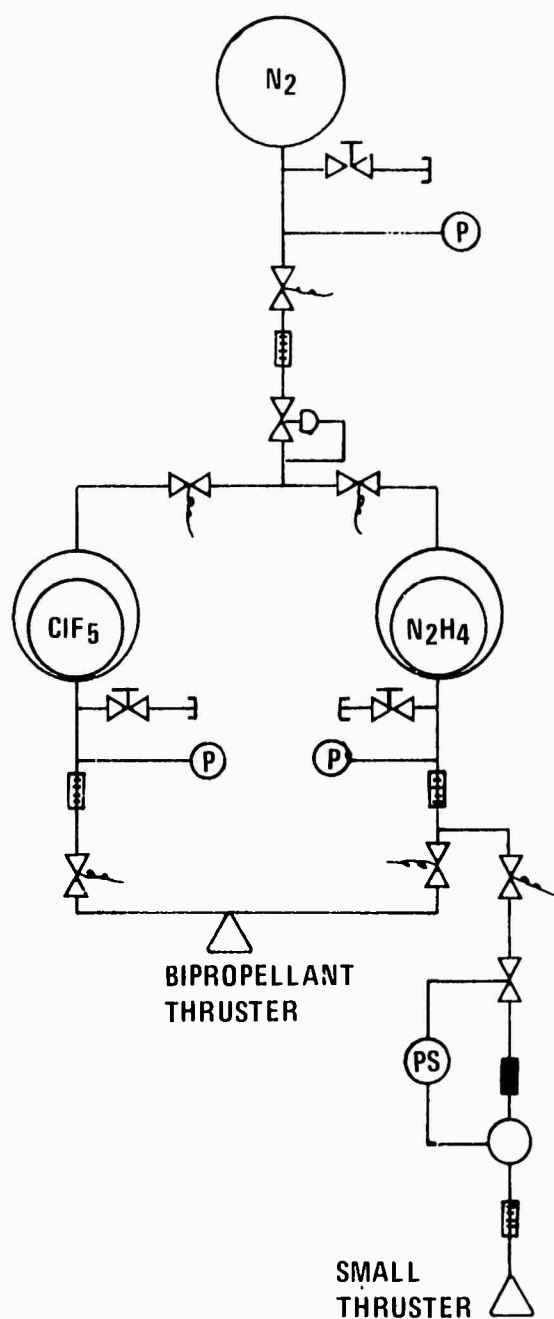
The development status of the decomposed ammonia radioisotope thruster (DART) has been described under Section III. B. 6. The all-DART concept has been favored by the AFRPL since 1968, and an in-house study was accomplished by Mr. E. Barth to detail its potentials and mission applications (Reference 5).

a. 5-lb<sub>f</sub> Thruster

There is no 5-lb<sub>f</sub> engine in this concept. All engines are of the 0.025-lb<sub>f</sub> class. Repositioning may pose a problem.

b. 0.025-lb<sub>f</sub> Thruster

The ADP DART performance goals were used for the all-DART system. Thrust level was 25 millipounds and a 20-millisecond pulse



	Weight (pounds)
Fill Valve	0.25
Transducer	0.20
Solenoid	0.20
Filter	0.20
Regulator	0.3
Solenoid (2)	0.4
Fill Valve (2)	0.50
Transducer (2)	0.40
Filter (2)	0.40
Solenoid (3)	0.60
Control Valve	0.40
Pressure Switch	0.25
G G	0.35
Plenum	0.30
Filter	0.20
Lines	1.00
Thrusters	
Large 8(1.30)	= 10.4
Small 12(.4)	= 4.8
Total Weight	<hr/> 21.15

Figure 27. System Schematic for  $\text{ClF}_5/\text{N}_2\text{H}_4\text{-N}_2\text{H}_4$  GG Plenum

produced a minimum impulse bit of  $5 \times 10^{-4}$  lb<sub>f</sub>-sec. Pulse mode Isp = 310 seconds and steady-state Isp = 280 seconds were used, based on a capsule gas temperature of 2500 °F.

#### c. Conceptual Schematic

Figure 28 shows the conceptual schematic.

### C. PROPULSION SYSTEM WEIGHT

A computer program was developed to facilitate the task of calculating spacecraft geometry, weighing the propellant required and sizing propellant tankage and pressurization systems. This program will weigh the entire propulsion system for a geosynchronous orbit with up to 10 different propulsion functions being performed. The program will accept variations in the following parameters: (1) satellite parameters such as initial gross weight, life, initial angular momentum and repositioning rate, (2) center-body parameters such as bulk density, geometry (i. e., spherical, cylindrical or rectangular) and L/D ratios, (3) solar panel variables such as ideal specific weight, percent life degradation, specific surface area and height-to-length ratio, and (4) parameters for the small thrusters such as minimum thrust level, minimum pulse width, deadband half-angle for accuracy and the minimum average angular rate for limit cycling. In addition to these, data on the propellant storage tank materials and their properties and storage pressures are required. The Isp which would be realized during each propulsion requirement for a given propellant or propellant combination is also required. Information obtained from the program is: (1) solar panel and centerbody dimensions and weights, (2) onboard power, (3) satellite moments of inertia, (4) impulse,  $\Delta V$  and propellant amounts for each propulsion requirement, (5) total impulse,  $\Delta V$  and propellant required for the mission, and (6) storage tank sizes and weights and the amount of pressurant required along with a tank to store it.

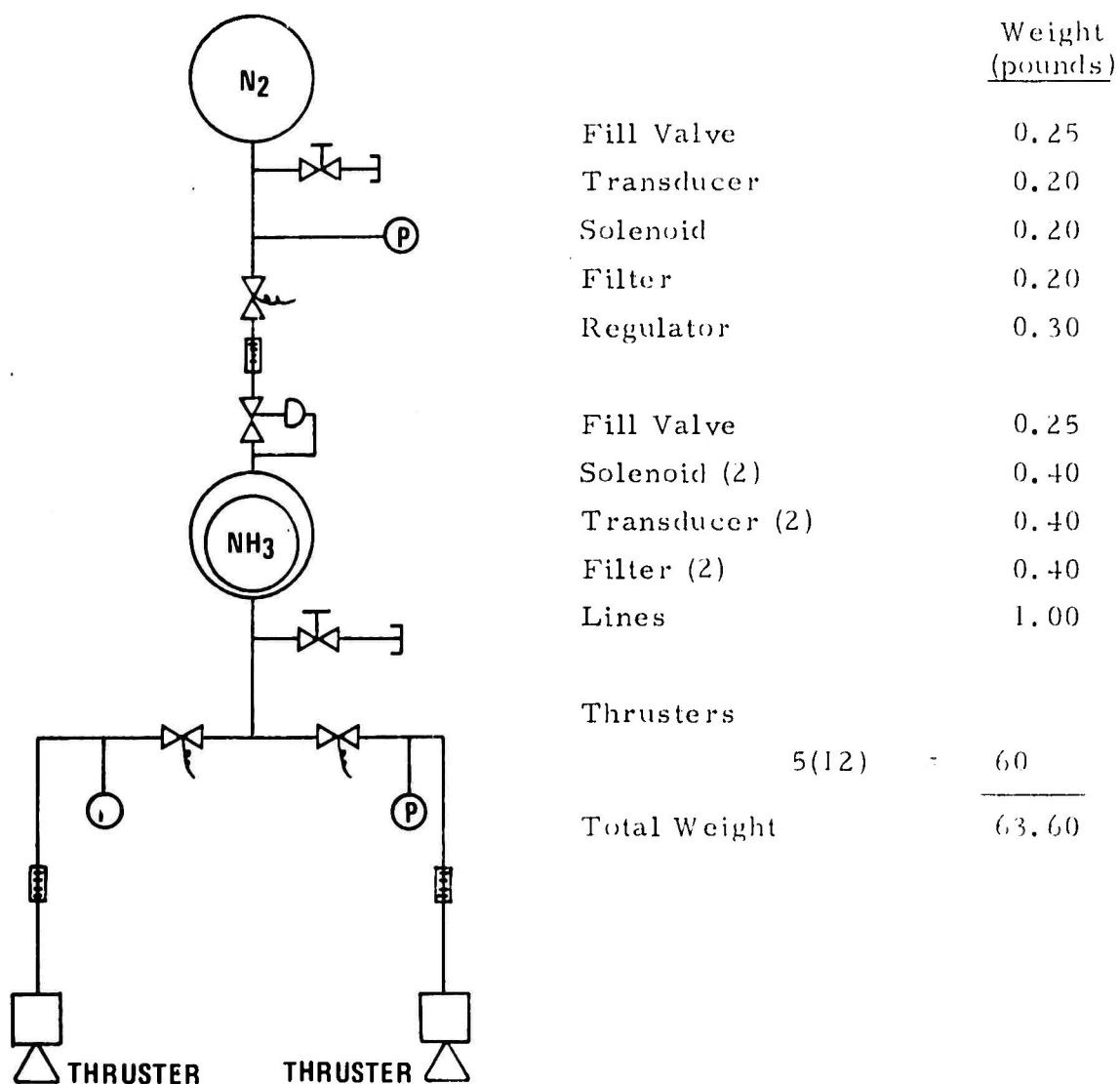


Figure 28. System Schematic for DART-DART

For this study, four different missions were analyzed. These were:

1. 10-year life, 3000-pound satellite performing north-south stationkeeping. (This mission will be designated as 10-3NS.)
2. 10-year life, 3000-pound satellite not performing north-south stationkeeping. (This mission will be designated as 10-3.)
3. 5-year life, 2000-pound satellite performing north-south stationkeeping. (This mission will be designated as 5-2NS.)
4. 5-year life, 2000-pound satellite not performing north-south stationkeeping. (This mission will be designated as 5-2.)

Values assumed for other spacecraft parameters which remain constant from system to system in this study have been discussed in Sections III-A-2 (Satellite Geometry) and III-A-3 (Mission Requirements). Tables IV, through VII present the results from the computer for the above four missions. These tables give the propellant weight, inert weight, total weight of the propulsion system without a power penalty, power penalty and the total system weight with the power penalty.

All of the systems investigated in this study require some power; some require more than others. All systems have solenoid valves in the feed systems and these require power to operate them. Since the power levels of these are so small, these power requirements were ignored in assessing a power penalty. It was also assumed that the hydrazine systems would not require heaters to keep the hydrazine as a liquid. Therefore, power penalties were assessed upon the water electrolysis, hydrazine resistojet, colloid, cesium and mercury pulsed plasma systems. Power penalties used are presented in Table VIII.

TABLE IV. PROPULSION SYSTEM WEIGHT FOR 3000-POUND  
SATELLITE WITH A 10-YEAR LIFE PERFORMING  
NORTH-SOUTH STATIONKEEPING

High Thruster	Low Thruster	Propellant Weight	Inert Weight	Total Weight W/O Power	Power Penalty	Total Weight With Power
H <sub>2</sub> O	Colloid	200.638	65.604	266.242	94.6	360.842
N <sub>2</sub> H <sub>4</sub> Cat. *	Cs Ion	188.820	89.097	277.917	198.0	475.917
DO	Colloid	227.357	54.655	282.012	92.4	374.412
N <sub>2</sub> H <sub>4</sub> Cat.	Colloid	243.969	47.083	291.052	92.4	383.452
N <sub>2</sub> H <sub>4</sub> Cat.	Hg P. P. **	243.969	50.181	294.150	132.0	426.150
H <sub>2</sub> O	H <sub>2</sub> O	622.212	66.969	689.181	2.2	691.381
DART	DART	621.055	112.420	733.475	-	733.475
N <sub>2</sub> H <sub>4</sub> Cat.	DART	640.693	97.554	738.247	-	738.247
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Radioisotope	751.936	65.551	817.487	-	817.487
ClF <sub>5</sub> /N <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> H <sub>4</sub> GG Plenum	776.006	57.489	833.495	-	833.495
N <sub>2</sub> O <sub>4</sub> /N <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> H <sub>4</sub> GG Plenum	794.055	60.957	855.012	-	855.012
N <sub>2</sub> H <sub>4</sub> /Cat.	N <sub>2</sub> H <sub>4</sub> /Resistojet	826.525	51.933	878.458	6.6	885.058
DO	DO	850.282	73.368	923.650	-	923.650
N <sub>2</sub> H <sub>4</sub> /Cat.	N <sub>2</sub> H <sub>4</sub> Cat.	1013.323	62.811	1076.134	-	1076.134
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Electrolytic	1031.291	64.715	1096.006	19.8	1115.806
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> GG Plenum	1070.732	66.732	1137.086	-	1137.086

\* N<sub>2</sub>H<sub>4</sub> Catalytic

\*\* Hg Pulsed Plasma

TABLE V. PROPULSION SYSTEM WEIGHT FOR 3000-POUND  
SATELLITE WITH A 10-YEAR LIFE NOT PERFORMING  
NORTH-SOUTH STATIONKEEPING

High Thruster	Low Thruster	Propellant Weight	Inert Weight	Total Weight W/O Power	Power Penalty	Total Weight With Power
H <sub>2</sub> O	Colloid	107,713	60,893	168,606	94.6	263,206
DO	Colloid	135,291	49,997	185,288	92.4	277,688
N <sub>2</sub> H <sub>4</sub> Cat.	Colloid	152,436	42,461	194,897	92.4	287,297
N <sub>2</sub> H <sub>4</sub> Cat.	Hg. P. P.	152,436	49,425	201,861	132.0	333,861
N <sub>2</sub> H <sub>4</sub> Cat.	Cs Ion	142,634	86,946	229,580	198.0	427,580
H <sub>2</sub> O	H <sub>2</sub> O	203,515	57,556	261,071	2.2	263,271
DART	DART	204,642	83,397	288,039	-	288,039
DO	DO	240,824	50,624	291,448	-	291,448
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Radioisotope	250,217	43,493	293,710	-	293,710
N <sub>2</sub> H <sub>4</sub> Cat.	DART	227,546	66,941	294,487	-	294,487
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Resistojet	298,369	29,162	327,531	6.6	334,131
ClF <sub>3</sub> /N <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> H <sub>4</sub> GG Plenum	337,498	41,189	378,687	-	378,687
N <sub>2</sub> <sup>19</sup> F <sub>4</sub> /N <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> H <sub>4</sub> GG Plenum	341,879	42,098	383,977	-	383,977
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> GG Plenum	374,084	37,432	411,516	-	411,516
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Cat.	110,020	37,760	147,780	-	447,780
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Electrolytic	480,295	42,078	522,373	19.8	542,173

TABLE VI. PROPULSION SYSTEM WEIGHT FOR 2000-POUND  
SATELLITE WITH A 5-YEAR LIFE PERFORMING  
NORTH-SOUTH STATIONKEEPING

High Thruster	Low Thruster	Propellant Weight	Inert Weight	Total Weight W/O Power	Power Penalty	Total Weight With Power
H <sub>2</sub> O	Colloid	95.842	60.788	156.630	94.6	251.230
DO	Colloid	113.987	49.070	163.057	92.4	255.457
N <sub>2</sub> H <sub>4</sub> Cat.	Colloid	125.266	40.955	166.221	92.4	258.621
N <sub>2</sub> H <sub>4</sub> Cat.	Hg P. P.	125.266	47.071	172.337	132.0	304.337
N <sub>2</sub> H <sub>4</sub> Cat.	Cs Ion	107.001	84.902	191.903	198.0	389.903
ClF <sub>5</sub> /N <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> H <sub>4</sub> GG Plenum	293.170	37.867	331.037	-	331.037
N <sub>2</sub> H <sub>4</sub> Cat.	DART	260.949	70.897	331.846	-	331.846
DART	DART	246.654	86.588	333.242	-	333.242
H <sub>2</sub> O	H <sub>2</sub> O	275.462	59.459	334.921	2.2	337.121
N <sub>2</sub> O <sub>4</sub> /N <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> H <sub>4</sub> GG Plenum	300.932	39.578	340.510	-	340.510
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Radioisotope	300.454	45.910	346.364	-	346.364
DO	DO	331.742	54.365	386.107	-	386.107
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Resistojet	377.696	32.846	410.542	6.6	417.142
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> GG Plenum	412.496	39.171	451.667	-	451.667
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Cat.	512.553	42.285	554.838	-	554.838
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Electrolytic	565.962	45.784	611.746	19.8	631.546



TABLE VII. PROPULSION SYSTEM WEIGHT FOR 2000-POUND  
SATELLITE WITH A 5-YEAR LIFE NOT PERFORMING  
NORTH-SOUTH STATIONKEEPING

High Thruster	Low Thruster	Propellant Weight	Inert Weight	Total Weight W/O Power	Power Penalty	Total Weight With Power
H <sub>2</sub> O	Colloid	64.581	58.712	123.293	94.6	217.893
DO	Colloid	83.015	47.013	130.028	92.4	222.428
N <sub>2</sub> H <sub>4</sub> Cat.	Colloid	94.475	38.910	133.385	92.4	225.785
N <sub>2</sub> H <sub>4</sub> Cat.	Hg P. P.	94.475	46.711	141.186	132.0	273.186
DO	DO	114.763	44.932	159.695	-	159.695
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Radioisotope	123.835	36.944	160.779	-	160.779
ClF <sub>5</sub> /N <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> H <sub>4</sub> GG Plenum	138.901	31.038	169.939	-	169.939
N <sub>2</sub> O <sub>4</sub> /N <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> H <sub>4</sub> GG Plenum	141.611	31.698	173.309	-	173.309
N <sub>2</sub> H <sub>4</sub> Cat.	DART	117.022	57.894	174.916	-	174.916
N <sub>2</sub> H <sub>4</sub> Cat.	Cs Ion	91.535	83.931	175.466	198.0	373.466
DART	DART	101.587	74.993	176.580	-	176.580
H <sub>2</sub> O	H <sub>2</sub> O	130.146	55.364	185.510	2.2	187.780
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> GG Plenum	160.191	27.020	187.211	-	187.211
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Resistojet	192.057	23.933	215.990	6.6	222.590
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Cat.	299.488	32.664	332.152	-	332.152
N <sub>2</sub> H <sub>4</sub> Cat.	N <sub>2</sub> H <sub>4</sub> Electrolytic	373.085	37.286	410.371	19.8	430.171

TABLE VIII. POWER PENALTY

<u>System</u>	<u>Penalty (pounds)</u>
Electrolytic	19.8
Resistojet	6.6
Cs Ion	198.0
Colloid	92.4
Hg P. P.	132.0
H <sub>2</sub> O	2.2

The ideal method of assessing a power penalty would be based on the continuous power required by a thruster. However, thruster requirements are given as, say, 100 watts. It is not stated if this is a continuous requirement or one that is required just during the pulse itself. Also, no information is given as to power required between pulses nor the amount of "warm-up" time required by a particular thruster. Therefore, power penalties were assessed on the basis of the amount of power required by a thruster times the number of thrusters onboard. The weight of a solar panel which would then provide this power was added to the propulsion system weight. In this manner, the maximum power penalty has been assessed upon the systems.

Figures 29 through 32 present the total propulsion system weights graphically. Figures 29 and 30 have no power penalties whereas Figures 31 and 32 include them. It should be noted that in each figure, the systems are arranged in order of increasing total weight for the mission with north-south stationkeeping.

Several observations are to be made from the two figures without power penalty. The most important is the large weight saving obtained when the small thruster is of the electric type and the mission requires north-south stationkeeping. In the case of a 10-year, 3000-pound satellite, this saving stands to be as much as 871 pounds between the  $N_2H_4$  catalytic- $N_2H_4$  gas generator (GG) plenum system and the  $H_2O$  electrolysis-colloid system, and as little as 395 pounds between the all- $H_2O$  electrolysis system and the  $N_2H_4$  catalytic-Hg pulsed plasma system. This weight jump between electric and chemical small thrusters is not very large for a mission which does not require north-south stationkeeping, but there still are savings with electric propulsion. It is interesting to note that in all four missions, the  $H_2O$  electrolysis-colloid is the lightest propulsion system combination. For missions 10-3NS and 10-3 (i.e., 10 years, 3000 pounds, with and without north-south), the all-water electrolysis system is the lightest of the chemical systems.

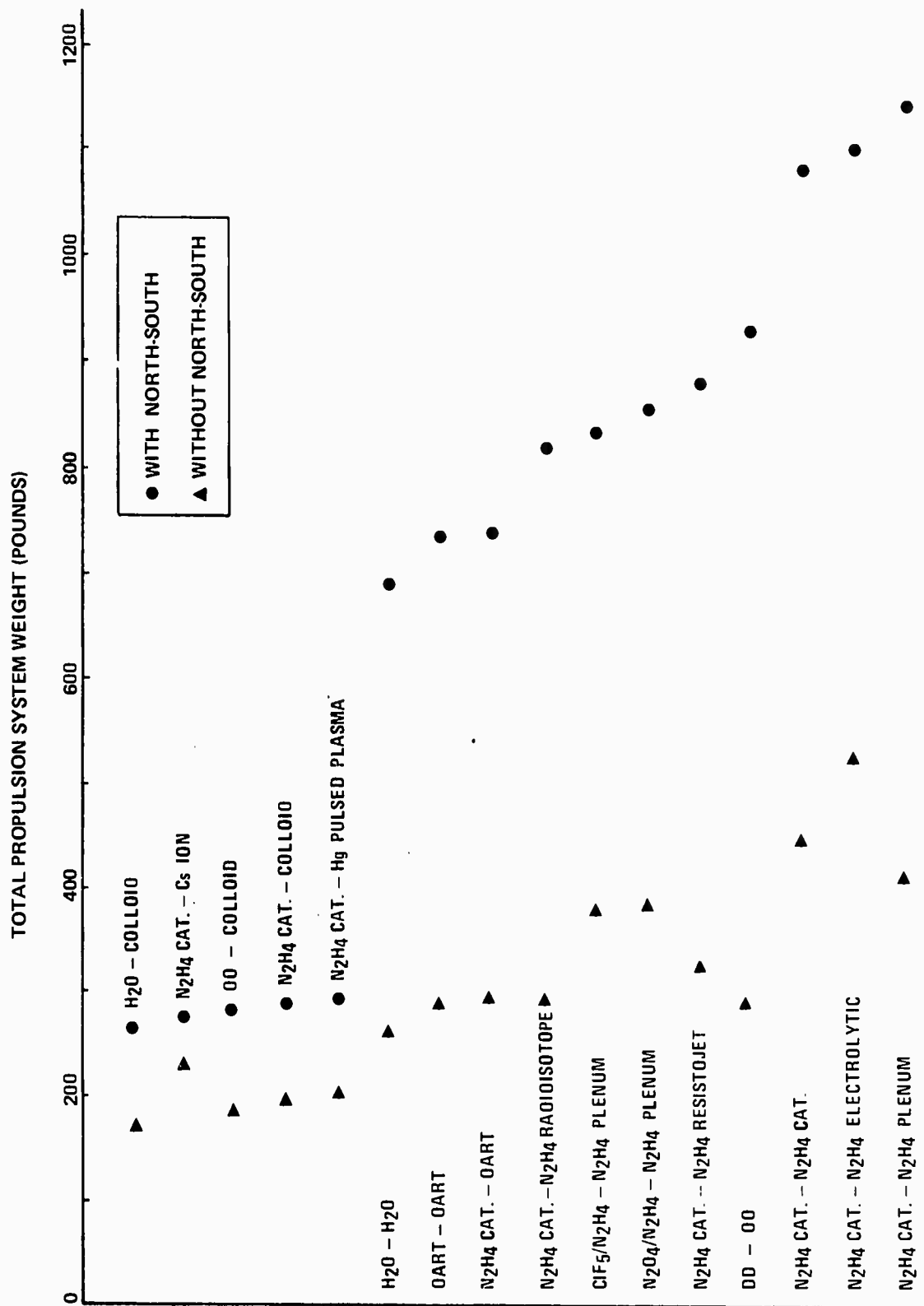


Figure 20. Propulsion System Weight for 3000-Pound, 10-Year Satellite Without Power Penalty

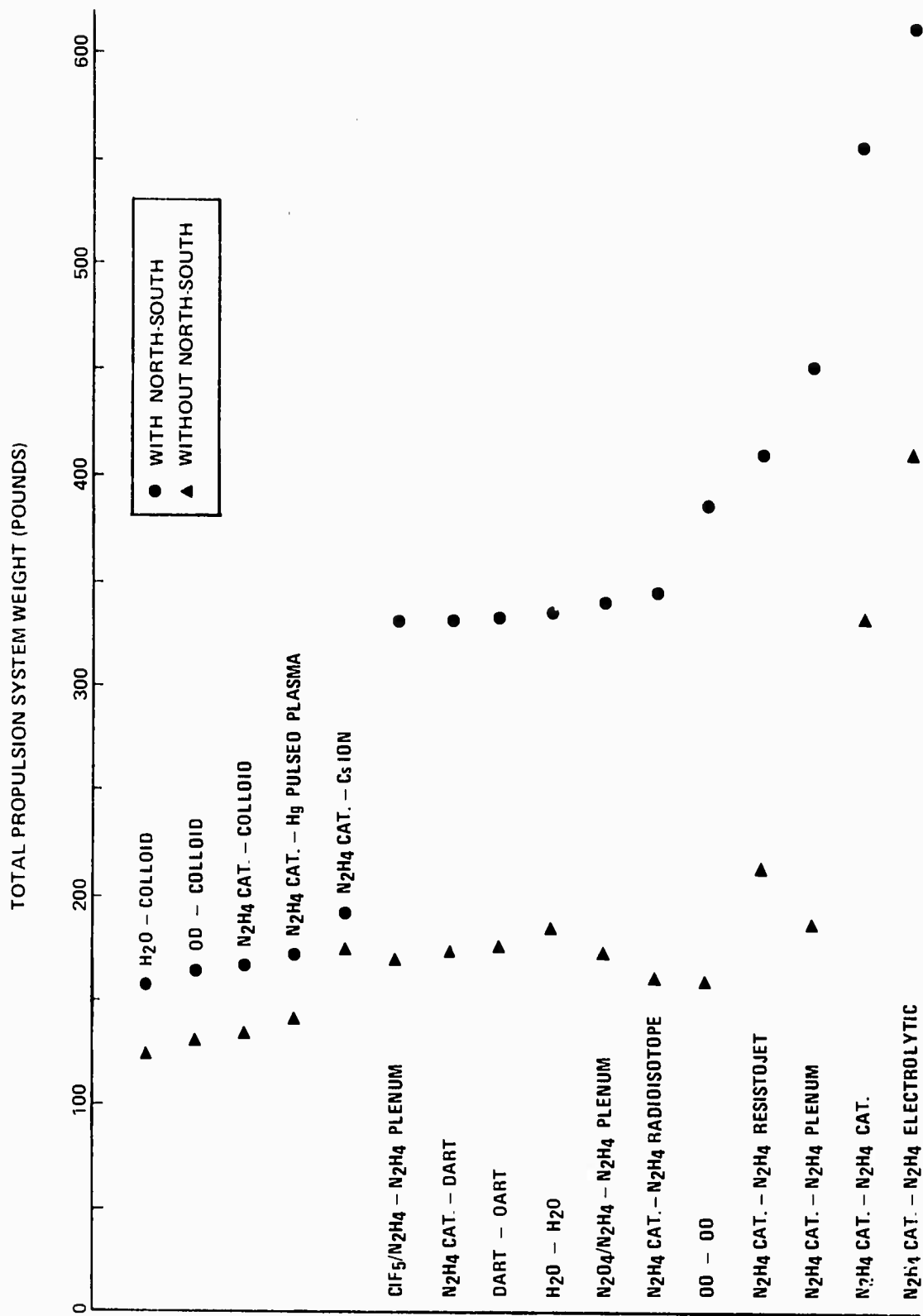


Figure 30. Propulsion System Weight for 2000-Pound, 5-Year Satellite Without Power Penalty

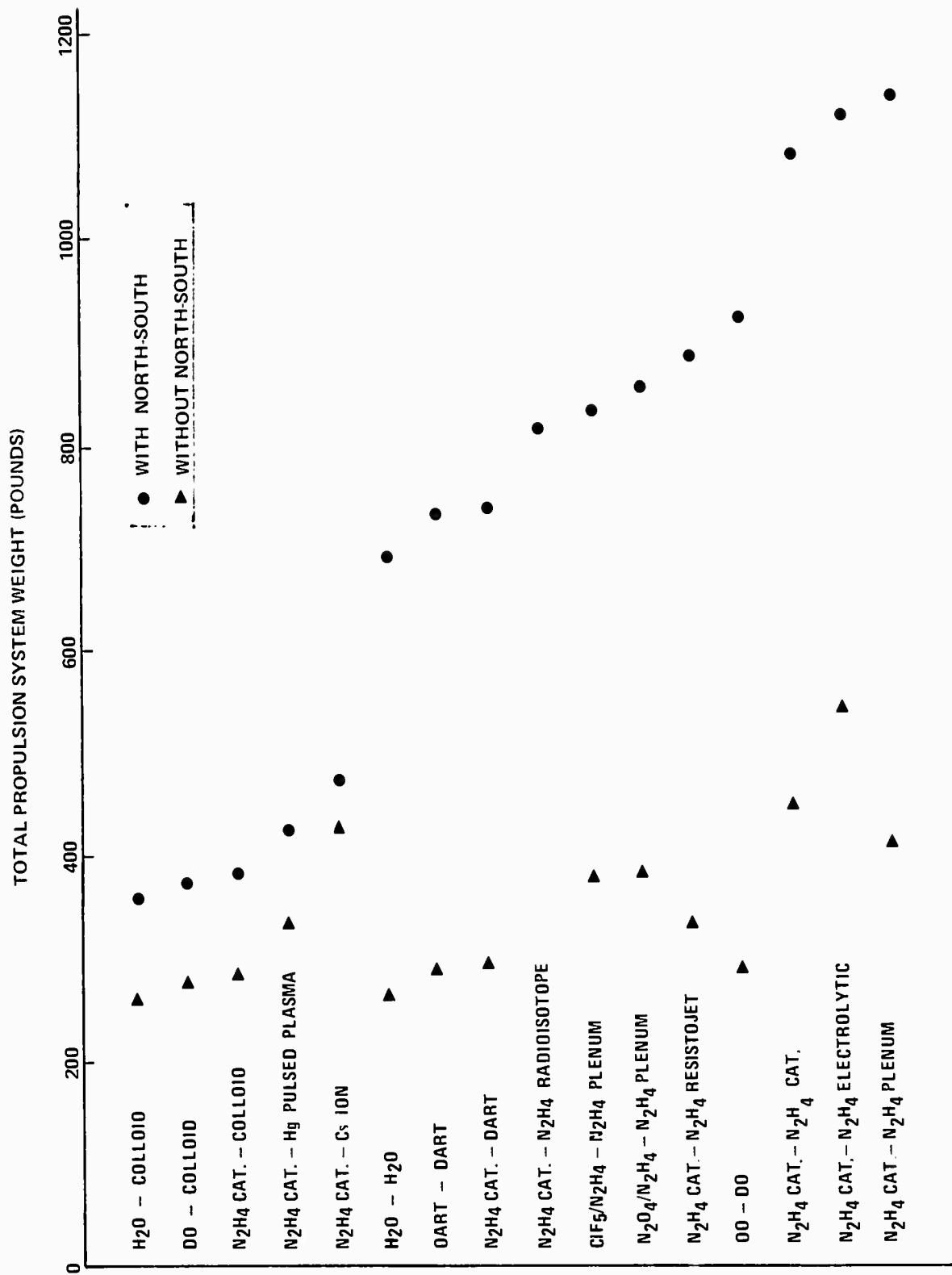


Figure 31. Propulsion System Weight for 3000-Pound, 10-Year Satellite With Power Penalty

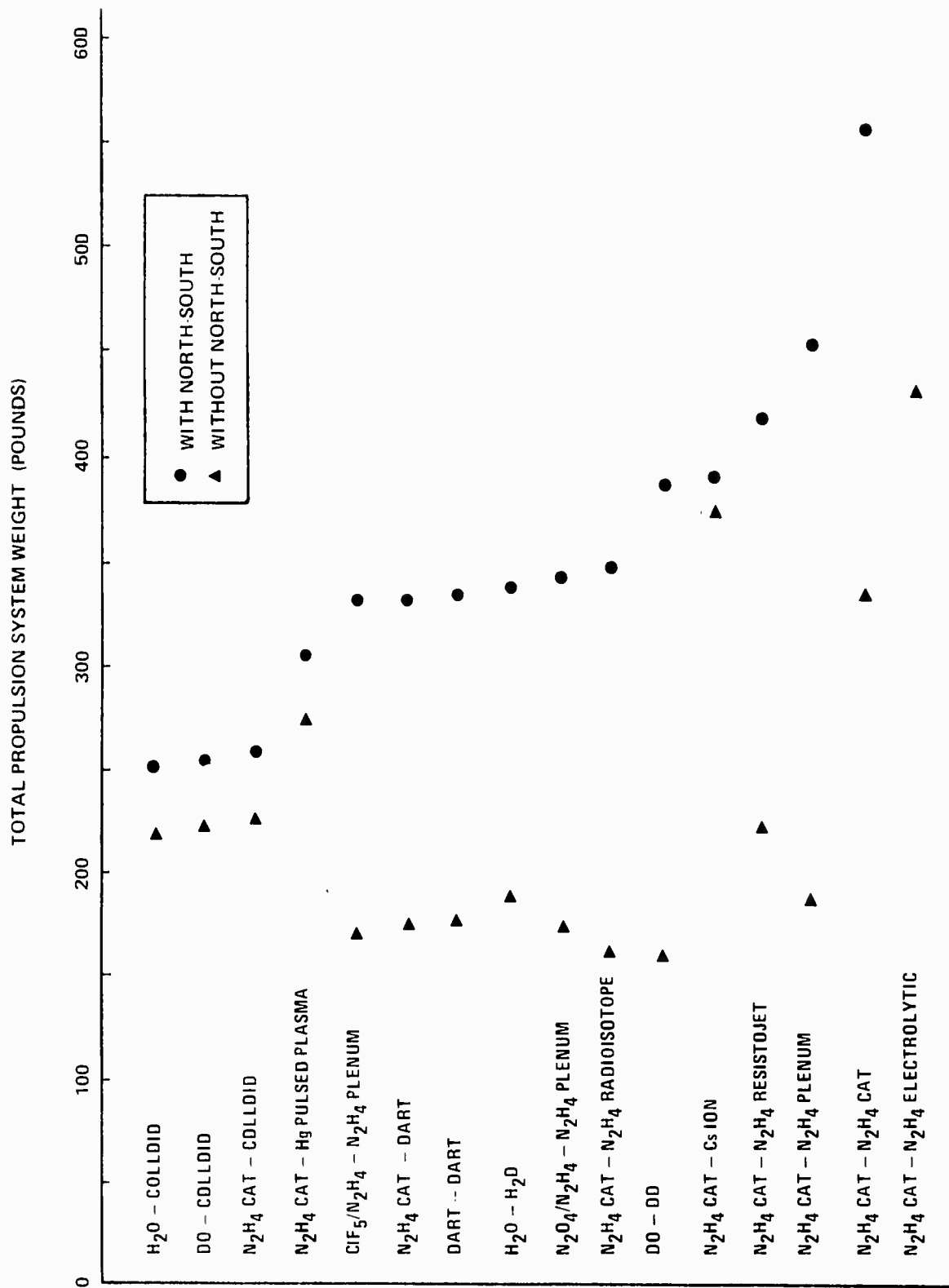


Figure 32. Propulsion System Weight for 2000-Pound, 5-Year Satellite With Power Penalty

For Mission 5-2NS, this system lacks only 4 pounds of being the lightest of all chemical systems. There are some systems which possess properties that translate themselves into total propulsion system weight handicaps for some of the missions investigated.

For Mission 10-3NS, the three systems, all  $N_2H_4$  catalytic,  $N_2H_4$  catalytic- $N_2H_4$  electrolytic and  $N_2H_4$  catalytic- $N_2H_4$  GG plenum, have approximately the same total propulsion system weight. However, this trend disappears in Mission 5-2NS and 5-2. For these missions, the  $N_2H_4$  catalytic- $N_2H_4$  GG plenum system is considerably lighter than the other two combinations. This is a result of the large minimum impulse bits required for  $N_2H_4$  catalytic or  $N_2H_4$  electrolytic small thrusters. Hence, for either of these two systems to be competitive for the less strenuous missions, i. e., without N-S stationkeeping, the minimum impulse bit must be reduced.

A similar circumstance occurs with the electric thrusters and in particular the  $N_2H_4$  catalytic-Cs ion system. However, in this case, the inert weight of the Cs ion thrusters and power-conditioning equipment is the reason for the increased weight. For the less strenuous missions, this inert weight begins to overshadow the propellant savings obtained with the large Isp of the Cs thruster when compared with the other electric systems.

There are several different observations to be made if a power penalty is included in the total system weight. These results are shown in Figures 31 and 32. The jump in system weight is not as large when going from electric to chemical. For Mission 10-3, there are several chemical systems which weigh less than the Hg pulsed plasma or cesium ion systems. For these two missions with the power penalty, the water electrolysis system is the lightest chemical system.



For Missions 5-2NS and 5-2, the effect of the power penalty on the Hg pulsed plasma and cesium ion engines is quite evident from Figure 32. For Mission 5-2NS, the weight of these two systems is comparable with the chemical systems whereas in Mission 5-2, most of the all-chemical systems weigh less than the electric systems. The water electrolysis-colloid system is the lightest for Mission 5-2NS, but for Mission 5-2, the all-DO system weighs less than any other one.

It is interesting to note that for all four missions investigated, the  $N_2H_4$  catalytic- $N_2H_4$  electrolytic system requires the most total impulse to do the same mission. It also requires the most  $\Delta V$  for mission accomplishment. The  $N_2H_4$  catalytic- $N_2H_4$  GG plenum will accomplish all four missions while expending the least amount of total impulse.

#### D. SYSTEM COSTS

The cost of a propulsion system is an important and integral part of a total system analysis. The development cost data for an advanced propulsion system are very difficult to obtain. In addition, a significant portion of the development cost is expended for flight qualification. The cost of a system not previously developed for a similar application will necessarily be higher than that of a system already flown. Therefore, the costs shown here reflect the total system cost even though it may have already been spent. Therefore, all values shown have a common basis. It should be stressed that these are rough cost estimates and should be considered as such. These estimates do have value in that they provide a relative ranking of a system's cost. Table IX provides the costs for the individual thruster concepts, while Table X gives the cost for an entire propulsion system combination.

## E. SYSTEM RELIABILITIES

Reliability data and combining techniques were used as suggested by a recent JPL report (Reference 2). Data presented in that report were derived from a review of previous reliability studies, reported component reliabilities and failure rate values. However, no failure rate data were included. Reliabilities for the noncyclic components were based on a 1-year mission duration, and the cyclic component reliabilities were used based on 10,000 cycles. Reliabilities were not improved through use of redundancy. A listing of component reliabilities used is provided in Table XI. Reliabilities used for the valve-thruster combinations are shown in Table XII.

TABLE IX. THRUSTER COSTS

	<u>Thruster</u>	<u>Cost</u>	<u>Where Obtained</u>
a.	<u>Large Thruster</u>	Million	
	$N_2H_4$ Cat.	2.5	AFRPL best estimate
	DO	3.0	AFRPL best estimate
	$H_2O$	5.0	Marquardt Corp. contract and AFRPL best estimate
	$N_2O_4/N_2H_4$	3.6	AFRPL best estimate
	$ClF_5/N_2H_4$	4.5	AFRPL best estimate
	DART	4.7	AFRPL best estimate and Reference 3
b.	<u>Small Thruster</u>		
	$N_2H_4$ Cat.	3.0	AFRPL best estimate
	$N_2H_4$ GG Plenum	3.5	AFRPL best estimate
	$N_2H_4$ Electrolytic	1.0	AFRPL best estimate

TABLE IX. THRUSTER COSTS (Cont)

<u>Thruster</u>	<u>Cost</u>	<u>Where Obtained</u>
b. <u>Small Thruster</u>		
$N_2H_4$ Resistojet	2.6	AFRPL best estimate and Reference 3
$N_2H_4$ Radioisotope	3.5	Reference 3
DART	4.7	AFRPL best estimate and Reference 3
Cs	4.0	AFAPL best estimate
Colloid	5.5	SAMSO ADP
Hg P. P.	4.85	AFAPL best estimate
DO	3.5	AFRPL best estimate
$H_2O$	5.5	Marquardt Corp. contract and AFRPL best estimate

TABLE X. TOTAL PROPULSION SYSTEM COST

<u>Large Thruster</u>		<u>Small Thruster</u>	<u>Total System Cost (millions)</u>
I	$N_2H_4$ Cat.	$N_2H_4$ Cat.	3.0
II	$N_2H_4$ Cat.	$N_2H_4$ GG Plenum	3.5
III	$N_2H_4$ Cat.	$N_2H_4$ Electrolytic	3.5
IV	$N_2H_4$ Cat.	$N_2H_4$ Resistojet	5.1
V	$N_2H_4$ Cat.	$N_2H_4$ Radioisotope	6.0
VI	$N_2H_4$ Cat.	DART	7.2
VII	$N_2H_4$ Cat.	Cs	6.5
VIII	$N_2H_4$ Cat.	Colloid	8.0
IX	$N_2H_4$ Cat.	Hg P. P.	7.35
X	DO	DO	3.5
XI	DO	Colloid	8.5
XII	$H_2O$	$H_2O$	5.0
XIII	$H_2O$	Colloid	10.5
XIV	$N_2O_4/N_2H_4$	$N_2H_4$ GG Plenum	7.1
XV	$ClF_5/N_2H_4$	$N_2H_4$ GG Plenum	8.0
XVI	DART	DART	4.7

TABLE XI. PROPULSION SYSTEM COMPONENT RELIABILITIES

Noncyclic Components

Filter	0.9999
Propellant Tank	0.9999
Plenum Tank	0.99988
Pressurization Gas Tank	0.99988
Line Heater	0.99985
Pressure Transducer	0.99980
Bladder	0.99968
Fill Valve	0.99910
Lines and Manifolds	0.99850

Cyclic Components

Gas Generator	0.9942
Electrolysis Cell	0.9925
Pressure Switch	0.9925
Relief Valve	0.9925
Regulator	0.9900
Solenoid Valve	0.9871
Bipropellant Solenoid	0.9830

TABLE XII. VALVE-THRUSTER RELIABILITY

Catalytic Monopropellant	0.9958
H <sub>2</sub> Electrolysis	0.9960
Bipropellant	0.9958
DART	0.9976
Monopropellant Plenum	0.9958
Electric Types	0.9970
Radioisotope Types	0.9976

The method used to obtain the reliability of each feed system employed the normal equation which is the product of all the component reliabilities raised to a power equal to the number of times that particular component appears in the system. The JPL report then suggests the following equations for the total system reliability.

1. The large thruster doing stationkeeping

$$R_{S_{LT}} = R_{F_{LT}} R_{V-T_{LT}}^4$$

where:

$$R_{S_{LT}} = \text{total large thruster system reliability}$$

$$R_{F_{LT}} = \text{large thruster feed system reliability}$$

$$R_{V-T_{LT}} = \text{large thruster - valve combination reliability}$$

2. The large thruster not doing stationkeeping

$$R_{S_{LT}} = R_{F_{LT}} R_{V-T_{LT}}^2$$

3. The small thruster doing stationkeeping

$$R_{S_{ST}} = R_{F_{ST}} R_{V-T_{ST}}^4$$

here:

$$R_{S_{ST}} = \text{total small thruster system reliability}$$

$$R_{F_{ST}} = \text{small thruster feed system reliability}$$

$$R_{V-T_{ST}} = \text{small thruster valve combination reliability.}$$

4. The small thruster not doing stationkeeping

$$R_{S_{ST}} = R_{F_{ST}} R_{V-T_{ST}}^2$$

Therefore, using these equations, a reliability for both the large thruster system and the small thruster system was obtained for each propulsion scheme. The propulsion systems can thus be ranked either according to the reliability of the large thruster or the reliability of the small thruster.

Table XIII shows the reliabilities for the large and small thruster feed systems and the total large and small thruster system. It should be pointed out that these numbers are based on the conceptual system schematics in the previous section, and therefore, are "conceptual reliabilities" only. However, they are useful from the standpoint of obtaining a relative ranking of the various propulsion schemes.

From Table XIII, the reliability ranking (high to low) for the large thruster feed systems may be summarized as in Table XIV.

TABLE XIII. SYSTEM RELIABILITY

Large Thruster	Small Thruster	Large Thruster		Small Thruster	
		Feed System	Total System	Feed System	Total System
$N_2H_4$ Cat.	$N_2H_4$ Cat.	0.95891	0.95087	0.95891	0.94290
$N_2H_4$ Cat.	$N_2H_4$ Plenum	0.95891	0.94290	0.93899	0.93412
$N_2H_4$ Cat.	$N_2H_4$ Electrolytic	0.95891	0.95087	0.95891	0.94741
$N_2H_4$ Cat.	$N_2H_4$ Resistojet	0.95891	0.95087	0.95891	0.94731
$N_2H_4$ Cat.	$N_2H_4$ Radioisotope	0.95891	0.95087	0.95891	0.94731
$N_2H_4$ Cat.	DART	0.94654	0.93860	0.94654	0.93748
$N_2H_4$ Cat.	Cs Ion	0.94654	0.93860	0.94658	0.93828
$N_2H_4$ Cat.	Colloid	0.94654	0.93860	0.94654	0.93823
$N_2H_4$ Cat.	Hg Pulsed Plasma	0.94654	0.93860	0.94654	0.93823
DO	DO	0.95891	0.94973	0.95891	0.94134
DO	Colloid	0.94654	0.94200	0.94654	0.93823
$H_2O$	$H_2O$	0.93202	0.91720	0.93202	0.92458
$H_2O$	Colloid	0.93202	0.92458	0.95891	0.94741
$N_2O_4/N_2H_4$	$N_2H_4$ Plenum	0.91940	0.90405	0.92678	0.91901
$ClF_5$	$N_2H_4$ Plenum	0.91940	0.90405	0.92678	0.91901
DART	DART	0.95891	0.95431	0.95891	0.94731



TABLE XIV. LARGE THRUSTER FEED SYSTEM  
RELIABILITY RANKING

<u>Type</u>	<u>Propellant</u>
Monopropellant	Same as in small thruster
Monopropellant	Different than in small thruster
Water Electrolysis	Same as in small thruster
Bipropellant	Fuel is same as small thruster propellant

A similar ranking for the small thruster feed system is in Table XV.

TABLE XV. SMALL THRUSTER FEED SYSTEM  
RELIABILITY RANKING

<u>Type</u>	<u>Propellant</u>
Monopropellant	Same as in large thruster
Monopropellant	Different than in large thruster
Plenum	Same as in monopropellant large thruster
Water Electrolysis	Same as in large thruster
Plenum	Same as fuel in bipropellant large thruster

These rankings serve to reiterate the obvious, that the more complicated or the more components in the feed system, the lower the reliability of that feed system. In like manner, large and small thruster total system reliability rankings may be obtained from Table XIII. For the large thruster, this ranking is shown in Table XVI.

TABLE XVI. TOTAL LARGE THRUSTER SYSTEM  
RELIABILITY RANKING

Type	Perform North-South	Propellant
Nuclear Thermal	No	Same as in small thruster
Catalytic	No	Same as in small thruster
Nuclear Thermal	Yes	Same as in small thruster
Catalytic	Yes	Same as in small thruster
Nuclear Thermal	No	Different than in small thruster
Catalytic	No	Different than in small thruster
H <sub>2</sub> O Electrolysis	No	Different than in small thruster
H <sub>2</sub> O Electrolysis	Yes	Same as in small thruster
Bipropellant	Yes	Fuel same as propellant in small thruster

The ranking for the small thruster system is in Table XVII.

TABLE XVII. TOTAL SMALL THRUSTER SYSTEM  
RELIABILITY RANKING

Type	Perform North-South	Propellant
Nuclear Thermal	No	Same as in large thruster
Nuclear Thermal	Yes	Same as in large thruster
Electric	Yes	Same as in large thruster
Catalytic	Yes	Same as in large thruster
Nuclear Thermal	Yes	Different than in large thruster
Electric	Yes	Different than in large thruster
Plenum	No	Same as in monopropellant large thruster
H <sub>2</sub> O	No	Same as in large thruster
Plenum	No	Same as fuel in bipropellant large thruster

These total system rankings once again point out the fact that the simpler the conceptual diagram, the more reliable the system should be. In addition, the nuclear thermal thruster is more reliable than the catalytic systems. It must be pointed out, however, that there is probably a difference in the reliability of the thrusters for the DO, DART and N<sub>2</sub>H<sub>4</sub> radioisotopes even though the value used for each is the same. The same applies to the electric-type thrusters. Common values were used because of the lack of data on these new thrusters. Therefore, care must be used in extracting just a number from these tables.

#### F. PLUME EFFECTS, INTEGRATION AND HANDLING

There are several other areas where the different combinations may be compared on a qualitative basis. One of these is plume effects. Two areas within plume effects warrant discussion. These are the signature of the plume and contamination of solar panels, and sensing devices by the plume. Table XVIII shows the propellants, their signatures and possible contaminations.

TABLE XVIII. PLUME EFFECTS

Propellant	Signature	Contamination
$N_2H_4$	Low	Low for short term; has not had long term studies done
$NH_3$	Low	Low
$H_2O$	High	High because of frozen water
$N_2O_4/N_2H_4$	High	High
$ClF_5/N_2H_4$	High	High
Cs	Low	Thought to be high but little data are available
Hg	Low	Same as Cs
Colloid	Low	Same as Cs
DO	High	High? No studies made

It must, however, be kept in mind that the contamination from any one of these propellants may be lowered by appropriate positioning of the thrusters or by careful tailoring of operating conditions. If the thrusters are pointed away from the solar panels and the sensors on the satellite, then there may be essentially no contamination from any of them. However,

from a plume effects standpoint, the all-hydrazine or ammonia systems will produce the least plume effects whereas the bipropellants and the water systems probably produce the worst effects. The cesium, mercury and colloid may produce the worst contaminations of all but this isn't really known because no real in-depth studies have been made using the propellants. In addition, since two of the missions investigated here are 10 years in length, it should be pointed out that no work has been done on long-term plume effects of this duration.

Integration and handling are two other areas where comparisons are required. The systems employing a radioisotope for a heat source have unique problems in that they require special handling both on the ground and within the spacecraft. Adequate shielding presents a problem because of the excessive weight buildup of the containers.  $\text{ClF}_5$  also has a ground-handling problem as a result of its corrosive and toxic nature.

Certain systems have inherent problems or lack flexibility. The cesium system is one of these because the entire feed system must be kept warm (above  $83.3^\circ\text{F}$ ) to avoid the problem of frozen cesium in the feed lines. If the cesium freezes, then the wicking process of feeding the thruster will not work. Hence, there are inherent problems in the feed system. Because of the electrolysis cell in the  $\text{H}_2\text{O}$  electrolysis system, there is very little flexibility. The cell must be sized to accomplish the task and cannot be split up in order to redistribute the weight throughout the satellite. Also, the storage of gaseous hydrogen and oxygen in the mixed condition presents a potentially explosive problem. Care must be exercised in this area.

The electrical systems (Cs, Hg and colloid) are very complex systems. They require large voltages and power. In addition, the action of the accelerated particles can degrade and limit the life of some of the engine parts.

## SECTION IV

### CONCLUSIONS AND RECOMMENDATIONS

Based upon the calculated data, several conclusions may be made. Conclusions as to system weight will be based on data including power penalty.

1. For the more strenuous missions, i. e., with north-south stationkeeping, the systems using an electric small thruster have a considerable weight saving. This is particularly true if the electric concept is a colloid system. The cesium and mercury pulsed plasma do not offer as large a weight saving, and in one case, none at all (cesium on a 5-year satellite).

2. For missions requiring no north-south stationkeeping, the electric systems offer no advantage from a weight standpoint. If the mission life is for 5 years or less, a considerable weight disadvantage is incurred as a result of the power penalty required.

3. The water electrolysis or nuclearthermal systems appear to offer some weight savings over the other "all-chemical" systems for the more strenuous missions. For the less strenuous mission, these systems are comparable in weight.

4. Although the all-hydrazine catalytic systems appear to offer no weight savings, the effect of the hydrazine plume is less than all other systems. Furthermore, because of the number of currently operational catalytic systems, further development and flight qualification are minimized.

5. If the actual power penalty is anywhere near that estimated, the electric systems offer no advantage for missions not requiring north-south stationkeeping.
6. The weight savings obtained for missions with no north-south stationkeeping indicate that development of an all-DO system is warranted.
7. The nuclearthermal systems appear to have very good reliability whereas the bipropellants and the water electrolysis system have worse reliabilities.
8. The reliabilities for solenoid valves are very poor and additional development in this area is needed. Also, considerable reliability work and life testing must be done in the electric thruster area.
9. The hydrazine electrolytic system suffers from a poor minimum impulse bit of  $0.005 \text{ lb}_f\text{-sec}$ . If this could be reduced to  $0.004 \text{ lb}_f\text{-sec}$ , then this concept may compare more favorably with the hydrazine catalytic systems.
10. The nuclearthermal systems have an integration and handling problem which must be solved.

The following recommendations are thus put forward.

1. Advanced development of the electric thrusters and, in particular, the colloid thruster
2. Life and reliability work on electric thrusters
3. Reduction of the power requirement of the electric thrusters

4. Development of the water electrolysis thrusters
5. Reduction of minimum impulse bit for the hydrazine electrolytic and the cesium ion thrusters
6. Development of DART and DO nuclearthermal thrusters
7. Improvement of valve reliability



APPENDIX A  
SATELLITE PROPULSION SYSTEM  
WEIGHT PROGRAM DESCRIPTION

The computer program can be divided into 15 distinct sections. This is shown on the overall logic diagram on the next page. The program calculates certain data in each of these sections. The flow through these sections is as shown in the diagram. Following the diagram is a short description of the calculations in each section.

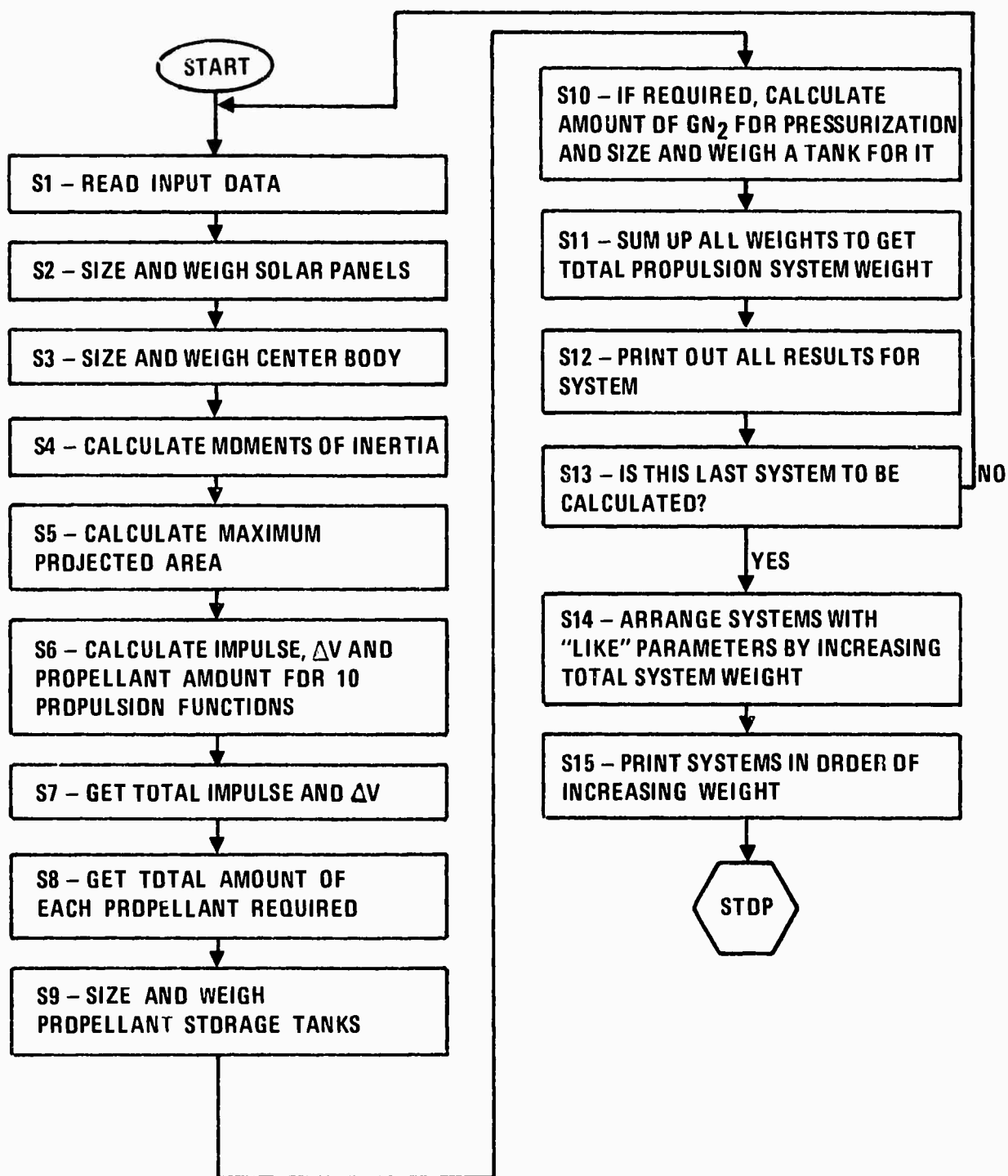


Figure 33. Logic Diagram for Computer Program

#### S1 - READ INPUT DATA

The data cards for a particular system are read into the computer.

#### S2 - SIZE AND WEIGHT SOLAR PANELS

The initial gross weight of the satellite is used to determine the onboard power from the solar panels using equation III-1 in the main body of this report. The panels are then sized and weighed using the ideal specific weight, percent life degradation, specific surface area and height-to-length ratio.

#### S3 - SIZE AND WEIGHT CENTERBODY

The centerbody weight is equal to the initial gross weight minus the weight of the solar panels. The centerbody can then be sized using the bulk density, centerbody shape code and the dimension ratios supplied as input.

#### S4 - CALCULATE MOMENTS OF INERTIA

The moments of inertia for the spacecraft are calculated here. Referencing the axis system as set up around the spacecraft in Figure 1 of the main body of this report, the equations for the moments of inertia in slug-ft<sup>2</sup> are:

For spherical centerbody:

$$I_{xx} = \frac{2}{5} M_{CB} \left( \frac{D}{2} \right)^2 + \frac{2}{3} M_{SP} Y_{SP}^2 + \frac{2}{3} M_{SP} \left( \frac{D}{2} \right)^2 \quad (A-1)$$

$$I_{yy} = \frac{2 M_{CB}}{5g} \left(\frac{D}{2}\right)^2 + \frac{2 M_{SP}}{3g} X_{SP}^2 - \frac{2 M_{SP}}{g} \left(\frac{X_{SP}}{2}\right)^2 \quad (A-2)$$

$$I_{zz} = \frac{2 M_{CB}}{5g} \left(\frac{D}{2}\right)^2 + \frac{2 M_{SP}}{12g} \left(Y_{SP}^2 + X_{SP}^2\right) + \frac{2 M_{SP}}{g} \left(\frac{D}{2} + \frac{Y_{SP}}{2}\right)^2 \quad (A-3)$$

where:

$M_{CB}$  = mass of centerbody

$M_{SP}$  = mass of solar panel

$D$  = centerbody diameter

Subscript CB = centerbody

SP = solar panel

For cylindrical centerbody:

$$I_{xx} = \frac{M_{CB}}{2g} \left(\frac{D}{2}\right)^2 + \frac{2 M_{SP}}{3g} Y_{SP}^2 + \frac{2 M_{SP}}{g} \left(\frac{D}{2}\right)^2 \quad (A-4)$$

$$I_{yy} = \frac{M_{CB}}{4g} \left[ \left(\frac{D}{2}\right)^2 + \frac{L^2}{3} \right] + \frac{2 M_{SP}}{3g} X_{SP}^2 - \frac{2 M_{SP}}{g} \left(\frac{X_{SP}}{2}\right)^2 \quad (A-5)$$

$$I_{zz} = \frac{M_{CB}}{4g} \left[ \left( \frac{D}{2} \right)^2 + \frac{L^2}{3} \right] + \frac{2 M_{SP}}{12g} \left( Y_{SP}^2 + X_{SP}^2 \right) \quad (A-6)$$

$$+ \frac{2 M_{SP}}{g} \left( \frac{D}{2} + \frac{Y_{SP}}{2} \right)^2$$

For rectangular centerbody:

$$I_{xx} = \frac{M_{CB}}{12g} \left( Z_{CB}^2 + Y_{CB}^2 \right) + \frac{2 M_{SP}}{3g} Y_{SP}^2 + \frac{2 M_{SP}}{g} \left( \frac{Y_{CB}}{2} \right)^2 \quad (A-7)$$

$$I_{yy} = \frac{M_{CB}}{12g} \left( X_{CB}^2 + Z_{CB}^2 \right) + \frac{2 M_{SP}}{3g} X_{SP}^2 + \frac{2 M_{SP}}{g} \left( \frac{X_{SP}}{2} \right)^2 \quad (A-8)$$

$$I_{zz} = \frac{M_{CB}}{12g} \left( X_{CB}^2 + Y_{CB}^2 \right) + \frac{2 M_{SP}}{12g} \left( Y_{SP}^2 + X_{SP}^2 \right) + \frac{2 M_{SP}}{g} \left( \frac{Y_{CB}}{2} + \frac{Y_{SP}}{2} \right)^2 \quad (A-9)$$

#### S5 - CALCULATE MAXIMUM PROJECTED AREA

This area is required in the calculation of solar pressure corrections and is the area seen when looking along the Z axis in Figure 1, including solar panel and centerbody projected area.

S6 - CALCULATE IMPULSE,  $\Delta V$  AND PROPELLANT AMOUNT FOR TEN MISSION FUNCTIONS

The ten mission functions are calculated in the following order where it has been assumed that the satellite is repositioned halfway through its lifetime. It is possible, however, to eliminate any number of these functions. In such a case, the computer automatically sets the impulse,  $\Delta V$  and propellant required to zero.

1. Despin
2. Tipoff
3. Injection
4. One-half of the total E-W stationkeeping
5. One-half of the total N-S stationkeeping
6. One-half of the total attitude maintenance, i. e., solar pressure, limit cycle and contingency.
7. Repositioning
8. One-half of the total E-W stationkeeping
9. One-half of the total N-S stationkeeping
10. One-half of the total attitude maintenance
11. Stationkeeping contingency

The method for calculating the impulse,  $\Delta V$  and amount of propellant for each propulsion function is as follows:

1. DESPIN

The impulse is calculated by dividing the satellite initial angular momentum by half the maximum distance between thrusters in the x-y plane (Figure 1). If the centerbody is a sphere or a cylinder, then this maximum distance is the diameter. If a rectangle, then use the largest dimension (y or z) of the centerbody.

The amount of propellant equals this impulse divided by the  $I_{sp}$  for this function, and the  $\Delta V$  required is obtained from the normal equation.

$$\Delta V = g \text{ Isp } \ln (M_o / M_e) \quad (\text{A-10})$$

where:  $M_o$  = mass of satellite at beginning of maneuver

$M_e$  = mass of satellite at end of maneuver

## 2. TIPOFF RATE

The impulse for tipoff is read into the computer as input data. The amount of propellant and  $\Delta V$  are then calculated as for Despin.

## 3. INJECTION ERROR

The  $\Delta V$  for this is read in as input data. The amount of propellant is determined through the use of equation A-10 and the impulse by multiplying the amount of propellant by the Isp.

## 4. EAST-WEST STATIONKEEPING

From Table I, the  $\Delta V$  is equal to

$$\Delta V = 7.15 t_m \quad (\text{A-11})$$

where  $t_m$  is the satellite life in years. The impulse and propellant are then calculated as an Injection Error.

## 5. NORTH-SOUTH STATIONKEEPING

From Table II, the  $\Delta V$  is equal to

$$\Delta V = 150 t_m$$

Impulse and propellant are as in east-west stationkeeping.

6. STATIONKEEPING CONTINGENCY

The amount of impulse is equal to 3 percent of the sum of the east-west impulse and the north-south impulse.  $\Delta V$  and propellant are then calculated as in Tipoff Rate.

7. SOLAR PRESSURE

The impulse is calculated from equation III-2 in the form

$$I_{t_s} = 5.91 t_m (0.35) A_{\perp}$$

where  $A_{\perp}$  = maximum projected area,  $\text{ft}^2$ . The  $\Delta V$  and propellant are then calculated as in Tipoff Rate.

8. LIMIT CYCLE

A value is calculated from both equation III-3 and equation III-4. The impulse required for limit cycling is then the larger of the two numbers.  $\Delta V$  and propellant are then calculated as in Tipoff Rate.

9. ATTITUDE MAINTENANCE CONTINGENCY

The impulse is calculated as per equation III-5 with  $\Delta V$  and propellant as per Tipoff Rate.

10. REPOSITIONING

The  $\Delta V$  is determined from equation III-7. Impulse and propellant are then calculated as per Injection Error.

S-7 - GET TOTAL IMPULSE AND  $\Delta V$

The total impulse and  $\Delta V$  are obtained by summing the impulse and  $\Delta V$  from each of the ten propulsion functions.



#### S-8 - GET TOTAL AMOUNT OF EACH PROPELLANT REQUIRED

In this section, the amount of each propellant used for the ten propulsion functions is summed. This section has the capability of handling a bipropellant large thruster. By using the mixture ratio on this, the two propellants can be split out to give correct propellant sums. An ullage of 1.5 percent is then added to each propellant sum.

#### S-9 - SIZE AND WEIGHT, PROPELLANT STORAGE TANKS

Spherical tanks are designed for propellant storage. They are sized by getting the total volume required from knowing the total propellant and the propellant density. The tanks are then weighed using the equation

$$\text{weight} = \frac{2\pi}{0.9} \frac{P R^3}{\sigma_y} \rho \quad (A-12)$$

where:  $P$  = operating pressure, psi  
 $R$  = tank radius, inches  
 $\rho$  = tank material density, lb/in.<sup>3</sup>  
 $\sigma_y$  = yield stress of tank material, psi

A safety factor of 1.25 is used in this calculation. From this weight, the thickness of the tank is determined. This thickness is then compared with that coming from the normal stress equation

$$T = \frac{P R}{2 \sigma_y} \quad (A-13)$$

The largest thickness is then selected and compared with the minimum average workable thickness (input data) for that particular metal. The largest of the three thicknesses is selected and the tank reweighed using this thickness. Then 15 percent of this weight is added to account for

fittings, flanges and attachment points. The program has the ability to not design a tank for any particular propellant if so desired.

S-10 - PRESSURIZATION SYSTEM

The program can design a pressurization tank, weigh it and weigh the gaseous nitrogen placed in it if so desired. It is also set up to pressurize only some of the propellant tanks. To simplify the calculations, an isothermal expansion of the  $\text{GN}_2$  was assumed.

S-11 - SUM UP ALL WEIGHTS TO GET A TOTAL PROPULSION SYSTEM WEIGHT

All weights are summed.

S-12 - PRINT OUT ALL RESULTS FOR SYSTEM

The results for the particular system just calculated are printed out.

S-13 - IS THIS LAST SYSTEM TO BE CALCULATED?

A check is made to see if there are more systems to be calculated. Up to 99 systems may be calculated with one computer run.

S-14 - ARRANGE SYSTEMS WITH "LIKE" PARAMETERS BY INCREASING TOTAL SYSTEM WEIGHT

Systems with common parameters (i. e., doing the same propulsion functions, having same initial gross weight and satellite life, etc.) are ranked according to increasing total propulsion system weight. If the computer received no inert weights (pipes, valves, thrusters, etc., as input data) for a particular system, then this system's total weight will appear as zero in the listing.

S-15 - PRINT SYSTEMS IN ORDER OF INCREASING WEIGHT

This increasing total weight listing is printed out.

APPENDIX B  
SATELLITE PROPULSION SYSTEM WEIGHT  
PROGRAM USER MANUAL

This section describes the procedure for writing the input required to use the computer to weigh the total propulsion system to accomplish the proposed post-1975 mission model. Twelve different types of input data cards are required to manipulate the program. Cards 2 through 12 describe any particular high-low thruster combination desired. Card 1 tells the computer how many such cases or combinations will be investigated. Up to 99 different combinations may be calculated during one computer run. However, a complete set of data cards (cards 2 through 12) must be furnished for each case. In the event of a special study involving relatively few changes on repeated cases, the original data deck for that case must be reproduced and only those cards containing changes must be repunched and inserted.

The input variables required by the program are defined on the following pages. This is followed by a listing of card formats and input instructions. Also included is a list of suggested values for some of the variables required by the program.

TABLE XIX. COMPUTER INPUT VARIABLES

C(i)	The <u>C</u> hemical used in a thruster
DBHAID	The <u>D</u> ead <u>B</u> and <u>H</u> alf <u>A</u> ngle <u>I</u> n <u>D</u> egrees
DEN(i)	The <u>D</u> ENsity of chemical C(i) in lbs/ft <sup>3</sup>
IDWHB	Means <u>D</u> o <u>W</u> e <u>H</u> ave a <u>B</u> ipropellant large thruster. Depending upon the value of IDWHB, the computer will decide whether there is a biprop or not
IDWPET(i)	Is a code that identifies which chemicals are expelled under pressure and which ones are not ( <u>D</u> o <u>W</u> e <u>P</u> ressurize <u>E</u> ach <u>T</u> ank)
IDWSEP(i)	Is a code which identifies which chemicals are stored in a tank and which ones are not ( <u>D</u> o <u>W</u> e <u>S</u> to <u>r</u> e <u>E</u> ach <u>P</u> ropellant in a tank)
IDWWP	This is a code which tells the computer <u>D</u> o <u>W</u> e <u>W</u> ant a <u>P</u> ressurization system
INOP	The <u>N</u> umber <u>O</u> f different <u>P</u> ropellant, C(i), in the system
INOSTR	The <u>N</u> umber <u>O</u> f <u>S</u> ystems <u>T</u> o <u>B</u> e <u>R</u> un or calculated. A system refers to a particular large-small thruster combination
IS(i)	A code which tells the computer which thruster (large or small) is used for mission function i
ISCBC	A code which tells the computer the geometry of the centerbody. (Satellite Center Body Code)
LL(i)	The number of systems which perform common mission functions
MM	A code which tells the computer whether to add inert weights or not
OPPRE	The initial storage <u>P</u> ressurant <u>P</u> REssure in psi

TABLE XIX. COMPUTER INPUT VARIABLES (Continued)

PTDEN	The density of the tank material used for storing a pressurant in $\text{lbs/in}^3$ ( <u>P</u> ressurant <u>T</u> ank <u>D</u> ENsity)
PTSIG	The yield stress of the tank material used for storing a pressurant in psi ( <u>P</u> ressurant <u>T</u> ank <u>S</u> IGma)
PWMIN	The minimum pulse width of the small thruster in seconds ( <u>P</u> ulse <u>W</u> idth <u>M</u> INimum)
SCBDEN	The <u>S</u> atellite <u>C</u> enter <u>B</u> ody bulk <u>D</u> ENsity in $\text{lbs/ft}^3$
SCBLOD	The <u>S</u> atellite <u>C</u> enter <u>B</u> ody <u>L</u> ength <u>O</u> ver <u>D</u> iameter if it is a cylinder and the Z/Y ratio if it is a rectangle
SCBZTX	The <u>S</u> atellite <u>C</u> enter <u>B</u> ody <u>Z</u> <u>T</u> o <u>X</u> ratio if it is a rectangle
SDV(3)	The <u>S</u> atellite <u>D</u> elta <u>V</u> elocity required for injection error in ft/sec
SIAM	The <u>S</u> atellite <u>I</u> nitial <u>A</u> ngular <u>M</u> omentum in ft-lb-sec
SIG(i)	The yield stress ( <u>S</u> IGma) for the storage tank material for chemical C(i) in psi
SISP(i)	Are the <u>S</u> ystem <u>I</u> SP's for a given propellant system for the 10 steps or functions required in the mission in sec
SIT(2)	The total impulse required for tipoff rate in $\text{lb}_f\text{-sec}$ ( <u>S</u> atellite <u>I</u> mpulse <u>T</u> otal)
SLIFE	The <u>S</u> atellite <u>L</u> IFE in years
SPHTL	The <u>S</u> olar <u>P</u> anel <u>H</u> eight <u>T</u> o <u>L</u> ength ratio
SPISW	The <u>S</u> olar <u>P</u> anel <u>I</u> deal <u>S</u> pecific <u>W</u> eight in $\text{lbs/kw}$
SPPCLD	The <u>S</u> olar <u>P</u> anel <u>P</u> er <u>C</u> ent <u>L</u> ife <u>D</u> egradation
SPSSA	<u>S</u> olar <u>P</u> anel <u>S</u> pecific <u>S</u> urface <u>A</u> rea in $\text{ft}^2/\text{kw}$
SREPRA	The <u>S</u> atellite <u>R</u> E <u>P</u> ositioning <u>R</u> At <u>e</u> in degrees/day

TABLE XIX. COMPUTER INPUT VARIABLES (Continued)

SUB(i)	The propellant ( <u>SUB</u> stance) or propellant combination used in a thruster
SWGT	Is the <u>Satellite WeiGhT</u> (initial gross weight) in pounds
TAMA(i)	The name of the storage <u>TAnk MATerial</u> for chemical C(i)
TAPR(i)	Is the storage <u>TAnk PRe</u> ssure for chemical C(i) in psi
THEDMI	The minimum achievable angular rate of the satellite for limit cycling in degrees/sec ( <u>THE</u> ta <u>Dot</u> <u>MIN</u> imum)
THRMIN	The small <u>THR</u> uster <u>MIN</u> imum thrust in $\text{lbs}_f$
TMDEN(i)	The storage <u>Tank Material DEN</u> sity for chemical C(i) in $\text{lbs/in}^3$
TMMT(i)	The minimum workable thickness for storage tank material TAMA(i) in inches ( <u>Tank MIN</u> imu <u>M</u> <u>T</u> hickness)
WGTI(i)	The inert weight of the propulsion system - includes, pipes, valves and thrusters in pounds ( <u>WGT</u> <u>I</u> ntert)

## INPUT DATA CARD FORMATS

<u>Card No.</u>	
1	Contol and Setup (3I12)
2	Large and Small Thruster Names [3 (3A6)]
3	Propellant Name and Propellant Density [3 (2A6), 3F10.3]
4	Propulsion Function and System Specification (10I2, 9X, 11, 9X, 11, 9X, 11, 10X, F6.3)
5	Propulsion Function Isp's (10F8.3)
6	General Satellite Specifications (5F10.4, 9X, 11, 2F10.4)
7	Solar Panel Specifications (4F10.4)
8	Thruster Specifications (F10.4, 3 F10.6, 2F10.4)
9	Propellant Storage Tank Materials [3 (2A6)]
10	Storage Tank Material Properties (3F10.3, 3F10.2, 3F6.4)
11	Pressurant Storage Tank Material Properties and Operating Pressures (2F10.3, F10.2, 3F10.3, 1X, 11, 1X, 11, 1X, 11, 5X, 11, 1X, 11, 1X, 11)
12	Thruster, Piping and Plumbing Weights (4F10.3, 1X, 11)

CARD NO. 1 (3112)  
CONTROL AND SETUP

<u>Variable</u>	<u>Columns</u>	<u>Remarks</u>
INØSTR	1-2	Place the total number of distinct system cases to be investigated in these two columns. The number must be right oriented. (Limited to 99)
LL (1)	3-4	Place the number of system cases that perform common mission functions here. The number must be right oriented.*
LL (2)	5-6	Place the number of systems cases in the second group which perform like mission functions here. The number must be right oriented.*
.	.	
.	.	
.	.	
.	.	
LL (30)	61-62	

---

\* At the end of the computer output, the computer ranks all system cases with common parameters (i.e., initial gross weight, life, etc.) or mission functions (i.e., north-south stationkeeping, repositioning, etc.) in order of ascending total propulsion system weight. These variables (LL (I) ) tell the computer how many system cases are in each common grouping. If LL(1) = 5 and LL(2) = 8, then the first 5 cases in the input cards will be ranked together and the next 8 input cases will be ranked together. There can be up to 30 such groupings.



CARD NO. 2 [3 (3A6)]

LARGE AND SMALL THRUSTER NAMES

This card can be filled out four different ways. Match the system to be investigated with either CASE A, B, C or D and input accordingly.

<u>Variable</u>	<u>Columns</u>	<u>Remarks</u>
<u>CASE A</u>	-	<u>The large thruster is a monopropellant. The small thruster is a monopropellant. The chemical used in the large thruster is not the same as that used in the small thruster.</u>
SUB(1)	1-18	Place a descriptor for the large thruster here. Example: CATALYTIC N2H4
SUB(2)	19-36	Place a descriptor for the small thruster here. Example: DART (NH3)
<u>CASE B</u>	-	<u>The large thruster is a monopropellant. The small thruster is a monopropellant. The chemical used in each thruster is the same.</u>
SUB(1)	1-18	Place a descriptor for the large thruster here. Example: CATALYTIC N2H4
SUB(2)	19-36	Place a descriptor for the small thruster here. Example: ELECTROLYTIC N2H4
<u>CASE C</u>	-	<u>The large thruster is a bipropellant. The small thruster is a monopropellant. The chemical in the monopropellant IS the same as the fuel in the bipropellant.</u>
SUB(1)	1-18	Place a descriptor for the bipropellant large thruster here. Example: NTO/HYDRAZINE
SUB(2)	19-36	Place a descriptor for the monopropellant small thruster here. Example: CATALYTIC N2H4
<u>CASE D</u>	-	<u>The large thruster is a bipropellant. The small thruster is a monopropellant. The chemical in the monopropellant is NOT the same as the fuel in the bipropellant.</u>
SUB(1)	1-18	Place a descriptor for the bipropellant large thruster here. Example: NTO/HYDRAZINE
	19-36	NOT USED
SUB(3)	37-54	Place a descriptor for the monopropellant small thruster here. Example: DART (NH3)

# CARD NO. 3 [ 3 (2A6), 3F10.3 ]

## PROPELLANT NAME AND PROPELLANT DENSITY

Fill out this card according to the instructions matching the case chosen for CARD 2.

Variable	Columns	Decimal Location	Remarks
<u>CASE A</u>			
C(1)	1-12	None	Place the chemical symbol here for the chemical used in the large thruster.
C(2)	13-24	None	Place the chemical symbol here for the chemical used in the small thruster.
	25-36		NOT USED
DEN(1)	37-46	COL. 43	The density of chemical C(1) in lb/ft <sup>3</sup>
DEN(2)	47-56	COL. 53	The density of Chemical C(2) in lb/ft <sup>3</sup>
<u>CASE B</u>			
C(1)	1-12	None	Place the chemical symbol here for the chemical used in both the large and small thruster.
	13-36		NOT USED
DEN(1)	37-46	COL. 43	The density of chemical C(1) is lb/ft <sup>3</sup>
<u>CASE C</u>			
C(1)	1-12	None	Place the chemical symbol here for the oxidizer in the large thruster bipropellant.
C(2)	13-24	None	Place the chemical symbol here for the fuel in the large thruster bipropellant
	25-36		NOT USED
DEN(1)	37-46	COL. 43	The density of the biprop oxidizer in lb/ft <sup>3</sup>
DEN(2)	47-56	COL. 53	The density of the biprop fuel in lb/ft <sup>3</sup>
<u>CASE D</u>			
C(1)	1-12	None	Place the chemical symbol here for the biprop oxidizer.
C(2)	13-24	None	Place the chemical symbol here for the biprop fuel.
C(3)	25-36	None	Place the chemical symbol here for the chemical in the monoprop small thruster.
DEN(1)	37-46	COL. 43	The density of the biprop oxidizer in lb/ft <sup>3</sup>
DEN(2)	47-56	COL. 53	The density of the biprop fuel in lb/ft <sup>3</sup>
DEN(3)	57-66	COL. 63	The density of the monoprop chemical in lb/ft <sup>3</sup>

Columns are numbered in column shown unless a decimal point is explicitly inserted in input.

CARD NO. 4 (10I2, 9X, 11, 9X, 11, 9X, 11, 10X, F6.3)

PROPULSION FUNCTION AND SYSTEM SPECIFICATION

<u>Variable</u>	<u>Columns</u>	<u>Decimal Location</u>	<u>Remarks</u>
IS(1)	1-2	None	Despin code*
IS(2)	3-4	None	Tipoff rate code*
IS(3)	5-6	None	Injection error code*
IS(4)	7-8	None	E-W stationkeeping code*
IS(5)	9-10	None	N-S stationkeeping code*
IS(6)	11-12	None	Stationkeeping contin- gency code*
IS(7)	13-14	None	Solar pressure code*
IS(8)	15-16	None	Limit cycle code*
IS(9)	17-18	None	Attitude maintenance contingency code*
IS(10)	19-20	None	Repositioning code*
	21-29		NOT USED
IDWHB	30	None	Bipropellant large thruster code**
	31-39		NOT USED
IDWWP	40	None	Pressurization code***
	41-49		NOT USED
INOP	50	None	Number of chemicals code****
	51-60		NOT USED
WGTR	61-66	COL 63	The mixture ration for the bipropellant large thruster. It must be written as the ratio of C(1)/C(2)

#### CARD 4 (cont)

\* These ten codes tell the computer which thruster (large or small) is used for each of the ten mission functions. If a function requires the large thruster, then  $IS(i) = 1$ . If a function requires the small thruster, then  $IS(i) = 2$  or  $3$  depending on whether SUB(2) or SUB(3) was used on Card 2. If it is desired to eliminate one of the ten functions from the system, then  $IS(i) = 0$  for that particular function. More than one propulsion function can be eliminated at once. All numbers must be right oriented in the fields.

\*\* = 0 if the large thruster is a monopropellant

= 1 if the large thruster is a bipropellant

\*\*\* = 0 if all of the system is a blowdown

= 1 if any part or all of the system is to be pressurized from a gas bottle

\*\*\*\* The total number of chemicals placed on Card 3

CARD NO. 5 (10F8.3)

PROPULSION FUNCTION Isp's

<u>Variable</u>	<u>Columns</u>	<u>Decimal Location</u>	<u>Remarks</u>
SISP(1)	1-8	COL 5	Despin Isp
SISP(2)	9-16	COL 13	Tipoff rate Isp
SISP(3)	17-24	COL 21	Injection error Isp
SISP(4)	25-32	COL 29	E-W stationkeeping Isp
SISP(5)	33-40	COL 37	N-S stationkeeping Isp
SISP(6)	41-48	COL 45	Stationkeeping contingency Isp
SISP(7)	49-56	COL 53	Solar pressure Isp
SISP(8)	57-64	COL 61	Limit cycle Isp
SISP(9)	65-72	COL 69	Attitude maintenance contingency Isp
SISP(10)	73-80	COL 77	Repositioning Isp

These are the 10 Isp values in seconds which are obtainable from the particular propellant(s) and the duty cycle for the 10 mission functions.

CARD NO. 6 (5F10.4, 9X, 11, 2F10.4)

General Satellite Specifications

<u>Variable</u>	<u>Columns</u>	<u>Decimal Location</u>	<u>Remarks</u>
SWGT	1-10	Col 6	The initial gross weight of the satellite in pounds.
SCBDEN	11-20	Col 16	The bulk density of the satellite centerbody is lb/ft <sup>3</sup>
SCBLØD	21-30	Col 26	If the centerbody of the satellite is a cylinder, then this is the L/D ratio. If the centerbody is a rectangle, then this ratio is the ratio of the dimensions of the end of the rectangle which faces the earth.
SCBZTX	31-40	Col 36	This is used only if the centerbody is a rectangle. It is the ratio of one side of the end of the rectangle to the length or height of the rectangle.
SLIFE	41-50	Col 46	The life of the satellite in years.
	51-59		Not used.
ISCBC	60	None	Centerbody shape code *
SIAM	61-70	Col 66	The satellite initial angular momentum in FT - LB - SEC
SREPRA	71-80	Col 76	The satellite repositioning rate in degrees per day.

- 1 if centerbody is a rectangle
- 2 if centerbody is a sphere
- 3 if centerbody is a cylinder

CARD NO. 7 (4F10.4)

Solar Panel Specifications

<u>Variable</u>	<u>Columns</u>	<u>Decimal Location</u>	<u>Remarks</u>
SPISW	1-10	Col 6	The solar panel ideal specific weight in LB/KW
SPPCLD	11-20	Col 16	The solar panel percent life degradation at the end of the satellite life.
SPSSA	21-30	Col 26	The solar panel specific surface area in FT <sup>2</sup> /KW.
SPHITL	31-40	Col 36	The ratio of the height of the solar panels (the side adjacent to the centerbody) to the length of the solar panel (the side perpendicular to the centerbody)

CARD NO. 8 (F10.4, 3F10.6, 2F10.4)

Thruster Specifications

<u>Variable</u>	<u>Columns</u>	<u>Decimal Location</u>	<u>Remarks</u>
THRMIN	1-10	Col 6	The minimum thrust of the thruster used for limit cycling in $LB_F$ .
PWMIN	11-20	Col 14	The minimum pulse width obtainable with the valving for the thruster used in limit cycling in seconds.
DBHAIID	21-30	Col 24	The dead band half-angle for limit cycling in degrees.
THEDMI	31-40	Col 34	The minimum achievable average angular rate in limit cycling in degrees per second.
SIT (2)	41-50	Col 46	The total impulse in LB-SEC required for tip-off rate.
SDV (3)	51-60	Col 56	The delta V in FT/SEC required for injection error.



CARD NO. 9 | 3 (2A6) |

Propellant Storage Tank Materials

<u>Variable</u>	<u>Columns</u>	<u>Remarks</u>
TAMA (1)	1-12	A descriptor for the tank material for storing C (1). Example: TITANIUM
TAMA (2)	13-24	A descriptor for the tank material for storing C (2).
TAMA (3)	25-36	A descriptor for the tank material for storing C (3).

CARD NO. 10 (3F10.3, 3F10.2, 3F6.4)

Storage Tank Material Properties

<u>Variable</u>	<u>Columns</u>	<u>Decimal Location</u>	<u>Remarks</u>
TMDEN (1)	1-10	Col 7	The density of tank material TAMA (1) in LB/IN <sup>3</sup>
TMDEN (2)	11-20	Col 17	The density of tank material TAMA (2) in LB/IN <sup>3</sup>
TMDEN (3)	21-30	Col 27	The density of tank material TAMA (3) in LB/IN <sup>3</sup>
SIG (1)	31-40	Col 38	The yield stress for tank material TAMA (1) in PSI
SIG (2)	41-50	Col 48	The yield stress for tank material TAMA (2) in PSI
SIG (3)	51-60	Col 58	The yield stress for tank material TAMA (3) in PSI
TMMT (1)	61-66	Col 62	The minimum workable thickness for tank material TAMA (1) in INCHES
TMMT (2)	67-72	Col 68	The minimum workable thickness for tank material TAMA (2) in INCHES
TMMT (3)	73-78	Col 74	The minimum workable thickness for tank material TAMA (3) in INCHES

CARD NO. 11 | 2F10.3, F10.2, 3F10.3, 3(1x, 11), 4x, 3(1x, 11) |

Pressurant Storage Tank Material Properties and Operating Pressures

<u>Variable</u>	<u>Columns</u>	<u>Decimal Location</u>	<u>Remarks</u>
ØPPRE	1-10	Col 7	The initial storage pressure of the pressurant (N <sub>2</sub> ) in PSIA.
PTDEN	11-20	Col 17	The density of 6AL-4V Titanium used as the tank material for the pressurant - This has a value of 0.161 LB/IN <sup>3</sup>
PTSIG	21-30	Col 28	The yield stress of the 6AL-4V Titanium used as the tank material for the pressurant - This has a value of 176,000 PSIA
TAPR (1)	31-40	Col 37	The storage pressure of chemical C (1) in PSIA
TAPR (2)	41-50	Col 47	The storage pressure of chemical C (2) in PSIA
TAPR (3)	51-60	Col 57	The storage pressure of chemical C (3) in PSIA
	61		Not used
IDWPET (1)	62	None	Pressurization code for chemical C (1) <sup>⊙</sup>
	63		Not used
IDWPET (2)	64	None	Pressurization code for Chemical C (2) <sup>⊙</sup>
	65		Not used

<u>Variable</u>	<u>Columns</u>	<u>Decimal Location</u>	<u>Remarks</u>
IDWPET (3)	66	None	Pressurization code for chemical C (3)*
	67-71		Not used
IDWSEP (1)	72	None	Storage tank code for Chemical C (1)**
	73		Not used
IDWSEP (2)	74	None	Storage tank code for chemical C (2)**
	75		Not used
IDWSEP (3)	76	None	Storage tank code for chemical C (3)**

---

\* 0 if chemical C(i) is pressurized from gas bottle  
1 if chemical C(i) is blown down

\*\* 0 if chemical C(i) is stored in a tank  
1 if chemical C(i) is not stored in a tank

CARD NO. 12 (4F10.3, 1X, 11)

Thruster, Piping and Plumbing Weights

<u>Variable</u>	<u>Columns</u>	<u>Decimal Location</u>	<u>Remarks</u>
WGTI (1)	1-10	Col 7	The inert weight (piping, valves, thrusters, etc.) of the system for one propellant tank per propellant
WGTI (2)	11-20	Col 17	Same as above for two tanks per propellant
WGTI (3)	21-30	Col 27	Same as above for three tanks per propellant
WGTI (4)	31-40	Col 37	Same as above for four tanks per propellant
	41		Not used
MM	42	None	Inert weight code*

\* = 0 if computer is to add these inert weights to propellant and tank weights  
= 1 if computer is not to add these inert weights

Some input variables have recommended values to be used. These variables and the values are listed below.

<u>Card No.</u>	<u>Variable</u>	<u>Value</u>
6	SCBDEN	20.0 lb/ft <sup>3</sup>
	SIAM	300.0 lb-ft-sec
	SREPRA	15.0 deg/day
7	SPISW	88.0 lb/kW
	SPPCLD	80.0 percent
	SPSSA	100.0 ft <sup>2</sup> /kW
8	DBHAID	0.125 deg (Coarse Mode)
		0.100 deg (Fine Mode)
	THEDMI	0.0002 deg/sec
	SIT (2)	23.0 lb/sec
	SDV (3)	50.0 ft/sec
11	PTDEN	0.161 lb/in <sup>3</sup>
	PTSIG	176,000.0 lbf/in <sup>2</sup>

It should be noted however, that it is not mandatory that any of the above values be used. These are only recommended as being representative values for a post-1975 SYNCSAT satellite.

This completes the input cards required to investigate one thruster combination. If a second system is desired, repeat cards 2 through 12 for system 2, and stack them immediately behind card 12 for system 1. Card 1 is not repeated, but the value of INOSTR just updated. The diagram on the next page demonstrates the stacking procedure required to calculate more than one propellant system and the control cards required by the IBM 7040 computer.

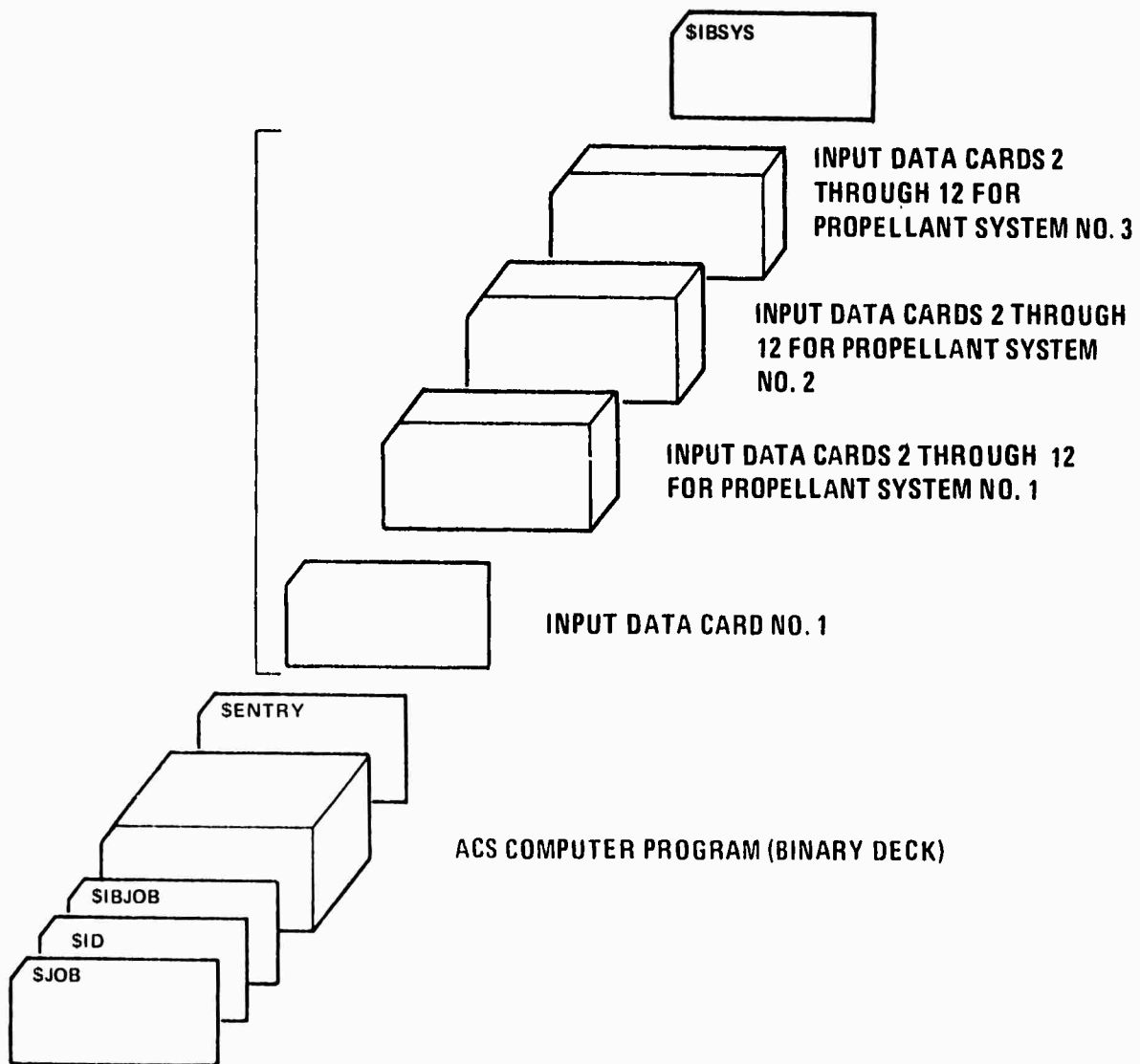


Figure 34. ACS Computer Program and Input Data Card Arrangement



The next page shows a sample propellant case. The large thruster is a bipropellant using  $\text{ClF}_5$  and  $\text{N}_2\text{H}_4$  with a mixture ratio of 2.0. The small thruster used for solar pressure corrections, limit cycling and attitude maintenance contingency is a  $\text{N}_2\text{H}_4$  gas generator plenum. The satellite initial gross weight is 3000 pounds and has a cylindrical center-body and square solar panels. The  $\text{ClF}_5$  is stored in a tank made of 301 cryostretched stainless steel, while the  $\text{N}_2\text{H}_4$  is stored in 6Al-4V titanium. Both are stored at 150 psi and the pressurant ( $\text{N}_2$ ) is stored at 3000 psi. The different values for Isp for the same propellant and thruster for different propulsion functions is a result of the duty cycles for the functions being different.

SAMPLE CASE INPUT CARDS

PROGRAM		FORTRAN CODING RECORD		DATE	
		CODED BY	DECK NUMBER	PAGE	OF PAGES
STMT NUMBER	COHT	FORTRAN STATEMENT			SERIAL NUMBER
1	1	N 2 H 4			175
2	2	N 2 H 4			176
3	3	N 2 H 4			177
4	4	N 2 H 4			178
5	5	N 2 H 4			179
6	6	N 2 H 4			180
7	7	N 2 H 4			181
8	8	N 2 H 4			182
9	9	N 2 H 4			183
10	10	N 2 H 4			184
11	11	N 2 H 4			185
12	12	N 2 H 4			186
13	13	N 2 H 4			187
14	14	N 2 H 4			188
15	15	N 2 H 4			189
16	16	N 2 H 4			190
17	17	N 2 H 4			191
18	18	N 2 H 4			192
19	19	N 2 H 4			193
20	20	N 2 H 4			194
21	21	N 2 H 4			195
22	22	N 2 H 4			196
23	23	N 2 H 4			197
24	24	N 2 H 4			198
25	25	N 2 H 4			199
26	26	N 2 H 4			200
27	27	N 2 H 4			201
28	28	N 2 H 4			202
29	29	N 2 H 4			203
30	30	N 2 H 4			204
31	31	N 2 H 4			205
32	32	N 2 H 4			206
33	33	N 2 H 4			207
34	34	N 2 H 4			208
35	35	N 2 H 4			209
36	36	N 2 H 4			210
37	37	N 2 H 4			211
38	38	N 2 H 4			212
39	39	N 2 H 4			213
40	40	N 2 H 4			214
41	41	N 2 H 4			215
42	42	N 2 H 4			216
43	43	N 2 H 4			217
44	44	N 2 H 4			218
45	45	N 2 H 4			219
46	46	N 2 H 4			220
47	47	N 2 H 4			221
48	48	N 2 H 4			222
49	49	N 2 H 4			223
50	50	N 2 H 4			224
51	51	N 2 H 4			225
52	52	N 2 H 4			226
53	53	N 2 H 4			227
54	54	N 2 H 4			228
55	55	N 2 H 4			229
56	56	N 2 H 4			230
57	57	N 2 H 4			231
58	58	N 2 H 4			232
59	59	N 2 H 4			233
60	60	N 2 H 4			234
61	61	N 2 H 4			235
62	62	N 2 H 4			236
63	63	N 2 H 4			237
64	64	N 2 H 4			238
65	65	N 2 H 4			239
66	66	N 2 H 4			240
67	67	N 2 H 4			241
68	68	N 2 H 4			242
69	69	N 2 H 4			243
70	70	N 2 H 4			244
71	71	N 2 H 4			245
72	72	N 2 H 4			246
73	73	N 2 H 4			247
74	74	N 2 H 4			248
75	75	N 2 H 4			249
76	76	N 2 H 4			250
77	77	N 2 H 4			251
78	78	N 2 H 4			252
79	79	N 2 H 4			253
80	80	N 2 H 4			254
81	81	N 2 H 4			255
82	82	N 2 H 4			256
83	83	N 2 H 4			257
84	84	N 2 H 4			258
85	85	N 2 H 4			259
86	86	N 2 H 4			260
87	87	N 2 H 4			261
88	88	N 2 H 4			262
89	89	N 2 H 4			263
90	90	N 2 H 4			264
91	91	N 2 H 4			265
92	92	N 2 H 4			266
93	93	N 2 H 4			267
94	94	N 2 H 4			268
95	95	N 2 H 4			269
96	96	N 2 H 4			270
97	97	N 2 H 4			271
98	98	N 2 H 4			272
99	99	N 2 H 4			273
100	100	N 2 H 4			274
101	101	N 2 H 4			275
102	102	N 2 H 4			276
103	103	N 2 H 4			277
104	104	N 2 H 4			278
105	105	N 2 H 4			279
106	106	N 2 H 4			280
107	107	N 2 H 4			281
108	108	N 2 H 4			282
109	109	N 2 H 4			283
110	110	N 2 H 4			284
111	111	N 2 H 4			285
112	112	N 2 H 4			286
113	113	N 2 H 4			287
114	114	N 2 H 4			288
115	115	N 2 H 4			289
116	116	N 2 H 4			290
117	117	N 2 H 4			291
118	118	N 2 H 4			292
119	119	N 2 H 4			293
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125	125	N 2 H 4			299
126	126	N 2 H 4			300
127	127	N 2 H 4			301
128	128	N 2 H 4			302
129	129	N 2 H 4			303
130	130	N 2 H 4			304
131	131	N 2 H 4			305
132	132	N 2 H 4			306
133	133	N 2 H 4			307
134	134	N 2 H 4			308
135	135	N 2 H 4			309
136	136	N 2 H 4			310
137	137	N 2 H 4			311
138	138	N 2 H 4			312
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147	147	N 2 H 4			321
148	148	N 2 H 4			322
149	149	N 2 H 4			323
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151	151	N 2 H 4			325
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153	153	N 2 H 4			327
154	154	N 2 H 4			328
155	155	N 2 H 4			329
156	156	N 2 H 4			330
157	157	N 2 H 4			331
158	158	N 2 H 4			332
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160	160	N 2 H 4			334
161	161	N 2 H 4			335
162	162	N 2 H 4			336
163	163	N 2 H 4			337
164	164	N 2 H 4			338
165	165	N 2 H 4			339
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170	170	N 2 H 4			344
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172	172	N 2 H 4			346
173	173	N 2 H 4			347
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184	184	N 2 H 4			358
185	185	N 2 H 4			359
186	186	N 2 H 4			360
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189	189	N 2 H 4			363
190	190	N 2 H 4			364
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192	192	N 2 H 4			366
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196	196	N 2 H 4			370
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210	210	N 2 H 4			384
211	211	N 2 H 4			385
212	212	N 2 H 4			386
213	213	N 2 H 4			387
214	214	N 2 H 4			388
215	215	N 2 H 4			389
216	216	N 2 H 4			390
217	217	N 2 H 4			391
218	218	N 2 H 4			392
219	219	N 2 H 4			393
220	220	N 2 H 4			394
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223	223	N 2 H 4			397
224	224	N 2 H 4			398
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229	229	N 2 H 4			403
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231	231	N 2 H 4			405
232	232	N 2 H 4			406
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234	234	N 2 H 4			408
235	235	N 2 H 4			409
236	236	N 2 H 4			410
237	237	N 2 H 4			411
238	238	N 2 H 4			412
239	239	N 2 H 4			413
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241	241	N 2 H 4			415
242	242	N 2 H 4			416
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252	252	N 2 H 4			426
253	253	N 2 H 4			427
254	254	N 2 H 4			428
255	255	N 2 H 4			429
256	256	N 2 H 4			430
257	257	N 2 H 4			431
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269	269	N 2 H 4			443
270	270	N 2 H 4			444
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272	272	N 2 H 4			446
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274	274	N 2 H 4			448
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276	276	N 2 H 4			450
277	277	N 2 H 4			451
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285	285	N 2 H 4			459
286	286	N 2 H 4			460
287	287	N 2 H 4			461
288	288	N 2 H 4			462
289	289	N 2 H 4			463
290	290	N 2 H 4			464
291	291	N 2 H 4			465
292	292	N 2 H 4			466
293	293	N 2 H 4			467
294	294	N 2 H 4			468
295	295	N 2 H 4			469
296	296				

A sample output from this program will be of the form as shown on the next three pages. The words shown on these pages are a part of the output also.

THIS SYSTEM IS COMPOSED OF THE FOLLOWING PROPELLANT(S)  
 LARGE THRUSTER CLF5/N2F4  
 SMALL THRUSTER N2F4 GG PLENUM

THE SATELLITE WEIGHT IS 3000.000 LBS

THE SATELLITE LIFE IS 10.00 YEARS

THE CL BOARD POWER IS 3.350 KW

THE SOLAR PANELS WEIGHT 368.500 POUNDS

THE SOLAR PANEL DIMENSIONS ARE  
 HEIGHT 12.742 FEET LENGTH 12.942 FEET

THE SOLAR PANEL SPECIFIC WEIGHT IS 110.000 LBS/KW

THE SOLAR PANEL SPECIFIC SURFACE AREA IS 100.00 FT<sup>2</sup>/KW

THE CENTER BODY IS A CYLINDER

THE SATELLITE CENTER BODY WEIGHTS 2631.500 POUNDS

THE SATELLITE CENTER BODY BULK DENSITY IS 20.00 LBS/FT<sup>3</sup>

ITS DIMENSIONS ARE  
 DIAMETER 4.375 FEET LENGTH 8.751 FEET

MAXIMUM PROJECTED AREA IS 373.288 SQUARE FEET

THE MINIMUM IMPULSE BIT FOR LIMIT CYCLING IS 0.0005000 LB-SEC

THE SATELLITE MOMENTS OF INERTIA IN SLUGS-FT<sup>2</sup> ARE  
 I(XX) I(YY) I(ZZ)  
 889.300 779.033 1796.791

THE MIXTURE RATIO FOR THE BIPROP IS 2.000

THE AMOUNTS OF PROPELLANT, IMPULSE AND DELV FOR THE MISSION ARE

FUNCTION	PROPELLANT	IMPULSE, SEC LRS	PROP	DELV, FT/SEC
TIPOFF RATE	CLF5/N2H4	23.000	C.107	0.247
INJECTION ERROR	CLF5/N2H4	4645.779	16.020	50.000
EAST-WEST S.K.	CLF5/N2H4	6143.465	22.340	71.500
NORTH-SOUTH S.K.	CLF5/N2H4	123593.968	426.186	1500.000
CONTINGENCY S.K.	CLF5/N2H4	3892.123	14.153	53.410
SCALAR PRESSURE	N2H4 GG PLENUM	7721.468	70.195	98.840
LIMIT CYCLE	N2H4 GG PLENUM	7510.052	68.273	97.483
CONTINGENCY	N2H4 GG PLENUM	7615.760	69.234	100.253
REPOSITIONING	CLF5/N2H4	22599.724	77.930	279.944

THE TOTAL IMPULSE REQUIRED FOR THE MISSION IS 183745.332 LB-SEC

THE TOTAL DELTA V REQUIRED FOR THE MISSION IS 2251.678 FT/SEC

TOTAL AMOUNTS OF PROPELLANT REQUIRED

PROPELLANT	WEIGHT, LBS
CLF5	376.774
N2H4	399.232

PROPELLANT TANK MATERIALS AND WEIGHTS IN POUNDS

PROPELLANT	TANK MATL	1 TANK	2 TANKS	3 TANKS	4 TANKS
CLF5	301 CRYC SS	8.97	11.30	12.94	14.24
N2H4	6AL-4V TITAN	13.33	16.80	19.23	21.16

PROPELLANT TANK DIAMETERS IN FEET

PROPELLANT	1 TANK	2 TANKS	3 TANKS	4 TANKS
CLF	1.3702	1.4844	1.2967	1.1782
N2H4	2.3033	1.8281	1.5970	1.4510

PRESSURANT IS N2

IT IS STORED AT 3000.00 PSI AND REQUIRES 7.870 LBS CF N2  
 THE TANK MATERIAL IS 6AL-4V TITANIUM  
 THE TANK WEIGHT IS 6.17 LBS AND TANK DIAMETER IS 1.0121 FEET

TOTAL SYSTEM WEIGHT AS FUNCTION OF NUMBER OF PROPELLANT TANKS

ONE TANK, LBS TWO TANKS, LBS THREE TANKS, LBS FOUR TANKS, LBS

212.345 818.142 822.208 825.445

THE INERT WEIGHTS AS A FUNCTION OF NUMBER OF PROPELLANT TANKS

ONE TANK, LBS TWO TANKS, LBS THREE TANKS, LBS FOUR TANKS, LBS

21.150 24.250 27.350 30.450

THE TOTAL PROPELLSION SYSTEM WEIGHT INCLUDING INERT WEIGHTS AS  
 A FUNCTION OF THE NUMBER OF STORAGE TANKS PER PROPELLANT ARE

ONE TANK, LBS TWO TANKS, LBS THREE TANKS, LBS FOUR TANKS, LBS

833.495 842.392 849.558 855.895

The following is a listing of the computer program.

```

01-200 10 LAUXHUF LK RZ
02-200
03-200
04-200
05-200
06-200
07-200
08-200
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11-200
12-200
13-200
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99-200

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DIMENSION XXXX(3)
DIMENSION LL(30)
DIMENSION S1GTLL(100),SLIFLL(100),ISCLL(100),ISLL(100,10)
1 FORMAT(3I12)
2 FORMAT(3A6,3A6,3A6)
3 FORMAT(2A6,2A6,2A6,3F10.3)
4 FORMAT(10I2,8X,12,8X,12,8X,12,9X,F6.3)
5 FORMAT(10F8.3)
6 FORMAT(5F10.4,8X,12,2F10.4)
7 FORMAT(4F13.4)
8 FORMAT(6F10.4)
9 FORMAT(2A6,2A6,2A6)
10 FORMAT(6F10.3,3F6.3)
11 FORMAT(6F10.3,3I2,4X,3I2)
12 FORMAT(1F1,5X,54HTHIS SYSTEM IS COMPOSED OF THE FOLLOWING PROPELLA
INT(5))
13 FORMAT(10X,14PLANET THRUSTER,5X,3A6)
14 FORMAT(10X,14HSPALL THRUSTER,6X,3A6)
15 FORMAT(/,5X,23HTHE SATELLITE WEIGHT IS,1X,F10.3,1X,3HLBS)
16 FORMAT(1F1,5X,63HTHE AMOUNTS OF PROPELLANT, IMPULSE AND DELV FOR T
HE MISSIC ARE)
17 FORMAT(/,5X,2DEFLECTION,7X,1CHPROP-LLANT,7X,35HIMPULSE, SEC LEO PER
1P DELV, FT/S-0)
18 FORMAT(/,5X,CHIEFSPIN,11X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
19 FORMAT(5X,11HTIPOFF RATE,6X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
20 FORMAT(5X,10HIMPERFOR EAP,2X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
21 FORMAT(5X,14PEAST-F,EST S.K.,3X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
22 FORMAT(5X,16HOUT TH-SOUTH S.K.,1X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
23 FORMAT(5X,16HOUT TH-CEV S.K.,1X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
24 FORMAT(5X,14HSOLAR PRESSURE,3X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
25 FORMAT(5X,11HLIFT CYCLE,6X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
26 FORMAT(5X,11HCONTINGENCY,6X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
27 FORMAT(5X,13HREPOSITIONING,6X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
28 FORMAT(/,5X,45HTH TOTAL IMPULSE REQUIRED FOR THE MISSION IS,1X,F1
11.3,11,6F10.4)
29 FORMAT(/,5X,45HTH TOTAL DELTA V REQUIRED FOR THE MISSION IS,1X,11
11.3,11,6F10.4)
30 FORMAT(/,5X,36HTOTAL AMOUNTS OF PROPELLANT REQUIRED)
31 FORMAT(/,5X,10HSPALLANT,5X,11HLIFT,11,1)
32 FORMAT(5X,2A6,3X,F8.3)

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[illegible]

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521 FORMAT(10X,4HDIAWETER,1X,F8.3,1X,4HFEET)
522 FORMAT(10X,2HDIAWETER,1X,F8.3,1X,4HFEET,9X,6HLENGTH,1X,F8.3,1X,4HF
1EET)
524 FORMAT(/,5X,25HMAXIMUM PROJECTED AREA 15,1X,F10.3,1X,11HSQUARE FEET
1T)
525 FORMAT(/,5X,44HMINIMUM IMPULSE BIT FOR LIMIT CYCLING 15,1X,F10
1.7,1X,6H13-SEC)
526 FORMAT(/,5X,49HMINIMUM SATELLITE MOMENTS OF INERTIA IN SLUGS-FI2 ARE)
527 FORMAT(12X,5H1(XX),5X,5H1(YX),6X,5H1(ZZ))
528 FORMAT(10X,F10.3,1X,F10.3,1X,F10.3,1X,F10.3)
529 FORMAT(/,5X,35HMINIMUM INERTIAL RATIO FOR THE SIMPOP 15,1X,F7.3)
530 FORMAT(4F10.3,12)
533 FORMAT(/,5X,61HMINIMUM INERT WEIGHTS AS A FUNCTION OF NUMBER OF PROPEL
LANT TANKS)
534 FORMAT(/,5X,61HMINIMUM TOTAL PROPELLION SYSTEM WEIGHT INCLUDING INERT
WEIGHTS AS,/,5X,60HMINIMUM FUNCTION OF THE NUMBER OF STORAGE TANKS PER
2PROPELLANT ARE)
535 FORMAT(1H1,7X,68HMINIMUM THRUSTER SMALL THRUSTER WEIGHT
1IMPULSE DELTA V,/)
537 FORMAT(5X,5A6,2X,3A6,1X,F9.3,1X,F11.3,1X,F11.3)
539 FORMAT(1H1,5X,54HMINIMUM FOLLOWING SYSTEMS HAVE GIVEN PARAMETERS WHICH
1FOLLOW)
542 FORMAT(/,5X,35HMINIMUM MISSION FUNCTIONS PERFORMED ARE)
545 FORMAT(/,5X,6HDESPIN)
592 FORMAT(/,5X,11HIDOFF RATE)
595 FORMAT(/,5X,15HINJECTION ERROR)
598 FORMAT(/,5X,14HEAST-WEST S.K.)
1001 FORMAT(/,5X,16HMINIMUM-SOUTH S.K.)
1004 FORMAT(/,5X,16HCONVINCING S.K.)
1007 FORMAT(/,5X,14HSLAR PRESSURE)
1010 FORMAT(/,5X,11HLIMIT CYCLE)
1013 FORMAT(/,5X,11HCONTINGENCY)
1016 FORMAT(/,5X,13HPOSITIONING)
546(,1) INGEST, (LL(1),I=1,30)
C INGEST IS NUMBER OF SYSTEMS TO BE CALCULATED
L=1
47 READ(5,2) (SUB(1,J),J=1,3), (SUB(2,J),J=1,3), (SUB(3,J),J=1,3)
READ(5,3) (C(1,J),J=1,2), (C(2,J),J=1,2), (C(3,J),J=1,2), (C(4,J),J=1,3)
1I=1,3)
READ(5,4) (IS(1),I=1,10), (IWHB,ICWAP,IWAP,WGTR

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```

SCBX=SCBZ/SCBZTX
SCBY=SCBZ/SCBLD
GO TC 534
532 SCBDIA=(SCBVOL*6./3.14159)**(1./3.)
GO TC 534
533 SCBDIA=(4.*SCHVOL/(SCHLOC#3.14159))**(1./3.)
SCHLEN=SCBLD*SCBDIA
C OBTAIN MOMENTS OF INERTIA
534 IF (ISCB-2) 535, 536, 537
535 SP1XX=(SCBWT/(12.*32.2))*(SCBZ**2.)+(SCBY**2.))+SPWGT*(SPY**2.)/
1(3.*32.2)+SPWGT*((SCBY/2.)*2.)/32.2
SP1YY=(SCBWT/(12.*32.2))*(SCBX**2.)+(SCBZ**2.))+SPWGT*(SPX**2.)/
1(3.*32.2)-SPWGT*((SPX/2.)*2.)/32.2
SP1ZZ=(SCBWT/(12.*32.2))*(SCBX**2.)+(SCBY**2.))+SPWGT/(12.*32.2
1)*((SPY**2.)+(SPX**2.))+SPWGT*((SCBY/2.+SPY/2.)*2.)/32.2
GO TC 534
536 SP1XX=(2.*SCBWT/(5.*32.2))*((SCBDIA/2.)*2.))+SPWGT*(SPY**2.)/(3.*
132.2)+SPWGT*((SCBDIA/2.)*2.)/32.2
SP1YY=(2.*SCBWT/(5.*32.2))*((SCBDIA/2.)*2.))+SPWGT*(SPX**2.)/(3.*
132.2)-SPWGT*((SPX/2.)*2.)/32.2
SP1ZZ=(2.*SCBWT/(5.*32.2))*((SCBDIA/2.)*2.))+SPWGT*((SPX**2.)+(SP
1Y**2.))/(12.*32.2)+(SPWGT/32.2)*((SCBDIA/2.+SPY/2.)*2.)
GO TC 534
537 SP1XX=(SCBWT/(2.*32.2))*((SCBDIA/2.)*2.))+SPWGT*(SPY**2.)/(3.*32.
12)+SPWGT*((SCBDIA/2.)*2.)/32.2
SP1YY=(SCBWT/(4.*32.2))*((SCBDIA/2.)*2.)+(SCBLEN**2.)/3.))+SPWGT*(
1SPX**2.)/(3.*32.2)-SPWGT*((SPX/2.)*2.)/32.2
SP1ZZ=(SCBWT/(4.*32.2))*((SCBDIA/2.)*2.)+(SCBLEN**2.)/3.))+SPWGT*(
1SPY**2.+SPX**2.)/(12.*32.2)+SPWGT*((SCBDIA/2.+SPY/2.)*2.)/32.2
C GET MAXIMUM PROJECTED AREA
538 IF (ISCB-2) 539, 540, 541
539 PA1AX=SCBY*SCBX+2.*ADCP
GO TC 542
540 PA1AX=3.14159*(SCBDIA**2.)/4.+2.*ADCP
GO TC 542
541 PA1AX=SCBDIA*SCHLEN+2.*ADCP
C CALCULATE IMPULSE FOR SOLAR PRESSURE, LIMIT CYCLE, ATTITUDE
C MAINTENANCE CONTINGENCY AND DESPIN
C CALCULATE DELTA V FOR C- STATION KEEPING, N-S STATION KEEPING
C AND COMPOSITION

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642 IF (IS(7)) 700, 700, 544
700 SIT(7)=0.0
    GO TO 546
644 SIT(7)=5.91*SLIP#0.35#P MAX
646 IF (IS(8)-2) 547, 548, 549
647 RX=SCBZ
    RY=SCRX
    SZ=(SCBX**2.+SCBY**2.+SCBZ**2.)*#0.5
    GO TO 550
648 SA=SCADIA
    RY=SA
    RZ=RX
    GO TO 550
649 RX=SCADIA
    RY=SCADIA
    RZ=(SCADIA**2.+SCADEN**2.)*#0.5
    SCVIL=TRAIL*#DUNIT
    IF (IS(8)) 701, 701, 702
701 SIT(8)=0.0
    GO TO 545
702 ABC=(SCMLI**2.)*SLIP#( Z/(SMIXX+SMIYY)+RY/(SMIXX+SMIZZ))+RX/(SMIY
    Y+SMIZZ)/(DCHAD*0.01745)
    DEF=4.*(TRAIL**2.)*SLIP#((SMIYY+SMIZZ)/RX+(SMIXX+SMIZZ)/RY+(SMIX
    X+SMIYY)/RZ)*0.01745/DCHAD
    IF (ABC-DEF) 551, 552, 552
651 SIT(8)=DEF#365.*24.*3600.
    GO TO 545
652 SIT(8)=ABC*365.*24.*3600.
645 IF (IS(9)) 703, 703, 544
703 SIT(9)=0.0
    GO TO 553
654 SIT(9)=0.5*(SIT(7)+SIT(8))
653 IF (IS(1)) 704, 704, 546
704 SIT(1)=0.0
    GO TO 555
656 IF (IS(8)-2) 557, 558, 558
657 IF (SCBY-SCBZ) 559, 560, 560
659 SIT(1)=SIAM#2./SCBZ
    GO TO 555
660 SIT(1)=SIAM#2./SCBY

```



```

WP7=WE5/WREP
WP(10)=WE6-WF7
WP6=WP7/WREP
WPI4=WP7-WP6
V9=WP7/WREP
WPI5=WP6-WP9
WPI3=WP9-WP13
WP(4)=WPI1+WPI4
WPI1=WP12+WPI5
SIT(4)=WP(4)*SISP(4)
SIT(1)=WP(5)-SIT(5)
SIT(6)=C.01*(SIT(4)+SIT(5))
WP(6)=SIT(6)/SISP(5)
SIT(3)=WP(6)*SISP(3)
SIT(10)=WP(10)*SISP(10)
WPI1=V9
IF WP I=1,10
45 SUMIT=SUMIT+SIT(I)
SITVP(L)=SUMIT
SUMV(1)=32.2*SISP(1)*ALOG(SWGT/WE1)
SUMV(2)=32.2*SISP(2)*ALOG(WP1/WE2)
SUMV(6)=32.2*SISP(6)*ALOG(WE10/(WE10-WP(6)))
SUMV(7)=32.2*SISP(7)*ALOG(WE5/(WE5-(WP(7)/2.)))+32.2*SISP(7)*ALOG(W
EP9/(WP9-(WP(7)/2.)))
SUMV(8)=32.2*SISP(8)*ALOG(WE5-(WP(7)/2.))/(WE5-(WP(7)/2.))-(WP(8)/2
1.)))+32.2*SISP(8)*ALOG(WE9-(WP(7)/2.))/(WE9-(WP(7)/2.))-(WP(8)/2.
2))
SUMV(5)=32.2*SISP(5)*ALOG(WE5-(WP(7)/2.))-(WP(8)/2.))/(WE5-(WP(7)/2
1.))-(WP(8)/2.))-(WP(9)/2.))+32.2*SISP(9)*ALOG(WE9-(WP(7)/2.))-(WP(8
2)/2.))/(WE9-(WP(7)/2.))-(WP(8)/2.))-(WP(9)/2.)))
SUMV=0.0
DO 49 I=1,10
49 SUMV=SUMV+SUMV(I)
SITVP(L)=SUMV
WPI3C I=1,4
50 SIT(I)=C.0
IF (INUP-2) 52, 53, 54
52 DO 55 I=1,10
55 SUM(I)=SUM(I)+SIT(I)
SUM(I)=SUM(I)+1.1*(SUM(I)/70.)

```



```

VCL(1)=SUM(1)/DEN(1)
GO TO 56
53 DO 57 I=1,10
  IF (IS(1)-2) 58,59,59
58 SUM(1)=SUM(1)+WP(I)
  GO TO 57
59 SUM(2)=SUM(2)+WP(I)
57 CONTINUE
  IF (IEAHE-1) 60,61,61
60 SUM(1)=SUM(1)+1.15*(SUM(1)/76.)
  SUM(2)=SUM(2)+1.15*(SUM(2)/76.)
  VCL(1)=SUM(1)/DEN(1)
  VCL(2)=SUM(2)/DEN(2)
  GO TO 56
-1 A=SUM(1)*WSTP/(1.+WSTP)
  B=SUM(1)-A
  SUM(1)=A
  SUM(2)=SUM(2)+B
  SUM(1)=SUM(1)+1.15*(SUM(1)/76.)
  SUM(2)=SUM(2)+1.15*(SUM(2)/76.)
  VCL(1)=SUM(1)/DEN(1)
  VCL(2)=SUM(2)/DEN(2)
  GO TO 56
54 DO 62 I=1,10
  IF (IS(1)-2) 63,63,64
63 SUM(1)=SUM(1)+WP(I)
  GO TO 62
64 SUM(3)=SUM(3)+WP(I)
62 CONTINUE
  SUM(2)=(1./(1.+WSTP))*SUM(1)
  SUM(1)=SUM(1)-SUM(2)
  DO 65 I=1,3
65 SUM(1)=SUM(1)+1.15*(SUM(1)/76.)
  DO 66 I=1,3
66 VCL(1)=SUM(1)/DEN(1)
56 CONTINUE
  NCA SIZE TANKAGE
  IF (IACP-2) 67,68,69
67 A=1
  GO TO 70

```

C

```

* = 1.2
60 TC 70
80 A=3
90 DO 71 I=1,
IF (IC-5*(I)-1) 200,251,2.1
251 60 252 K=1,4
TDA(I,K)=2.0
252 TWGT(I,K)=3.0
260 IF 71
DO 72 I=1,
TDA(I,1)=(VOL(I)*3.14159)**(1./3.)
TDA(I,2)=(2.*3.14159*(TDA(I,1)**2.)*TAPR(I)*TMDEN(I)*1.25)/
(0.9*SIG(I))
T1=TWGT(I,1)/(TMDEN(I)*3.14159*(TDA(I,1)**2.))
T2=TAPR(I)*TDA(I,1)*3.14159*(TDA(I,1)**2.))
IF (T2-T1) 200,201,2.1
200 IF (T1-TMDEN(I))*3.14159,72,72
201 T=TMDEN(I)
60 TC 203
201 IF (T2-TMDEN(I))*202,73,73
72 TWGT(I,1)=1.15*TMDEN(I,1)
TDA(I,2)=(VOL(I)*3.14159)**(1./3.)
TDA(I,2)=(2.*3.14159*(TDA(I,2)**2.)*TAPR(I)*TMDEN(I)*1.25)/
(0.9*SIG(I))
TDA(I,3)=(VOL(I)*3.14159)**(1./3.)
TWGT(I,3)=(2.*3.14159*(TDA(I,3)**2.)*TAPR(I)*TMDEN(I)*1.25)/
(0.9*SIG(I))
TDA(I,4)=(VOL(I)*3.14159)**(1./3.)
TDA(I,4)=(2.*3.14159*(TDA(I,4)**2.)*TAPR(I)*TMDEN(I)*1.25)/
(0.9*SIG(I))
60 TC 71
70 T=1.25*T2
203 TWGT(I,1)=3.14159*(12.*TDA(I,1)**2.)*TMDEN(I)*1.15
TDA(I,2)=(VOL(I)*3.14159)**(1./3.)
TWGT(I,2)=3.14159*(12.*TDA(I,2)**2.)*TMDEN(I)*1.15*2.
TDA(I,3)=(VOL(I)*3.14159)**(1./3.)
TWGT(I,3)=3.14159*(12.*TDA(I,3)**2.)*TMDEN(I)*1.15*2.
TDA(I,4)=(VOL(I)*3.14159)**(1./3.)
TWGT(I,4)=3.14159*(12.*TDA(I,4)**2.)*TMDEN(I)*1.15*4.
71 CONTINUE
DO 74 I=1,4

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```

74 STW(I)=0.0
DO 75 I=1,N
  STW(1)=STW(1)+TWGT(I,1)
  STW(2)=STW(2)+TWGT(I,2)
  STW(3)=STW(3)+TWGT(I,3)
  STW(4)=STW(4)+TWGT(I,4)
75 SIZE PRESSURIZATION SYSTM AND WEIGHT IT
  DO 260 I=1,INBP
    IF(IENPET(I)-1)260,261,261
  261 TAPR(I)=0.0
  260 CONTINUE
  IF(ICWMP-1)76,77,77
  77 IF(INCP-2)79,80,81
  79 V=TAPR(1)*VOL(1)/(OPPRE-TAPR(1))
  V=1.05*V
  GO TO 82
80 V=(TAPR(1)*VOL(1)/(OPPRE-TAPR(1)))+(TAPR(2)*VOL(2)/(OPPRE-TAPR(2))
  V=1.05*V
  GO TO 82
81 V=(TAPR(1)*VOL(1)/(OPPRE-TAPR(1)))+(TAPR(2)*VOL(2)/(OPPRE-TAPR(2))
  V=1.05*V
82 PTDIA=(V*6./3.14159)**(1./3.)
PTWGT=(2.*3.14159*((6.*PTDIA)**3.)*OPPRE*PTUEN*1.25*1.15)/(1.9*PTSI
IC)
ANZ=OPPRE*V*2*./5774.2
OUT SYSTM TGTAL WEIGHT
DO 83 I=1,4
83 TOTSUM(I)=0.0
A=0.0
DO 84 I=1,N
84 A=A+STW(I)
DO 85 I=1,4
85 TOTSUM(I)=A+STW(I)
IF(ICWMP-1)86,87,87
87 DO 86 I=1,4
  TOTSUM(I)=TOTSUM(I)+WN2+PTWGT
80 CONTINUE
WRITE(6,12)

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WRITE(6,13) (SUB(1,J),J=1,3)
DO 900 J=1,3
  DO 901 J=1,3
    IF (IACJ-2) 22,28,29
  22 WRITE(6,14) (SUB(2,J),J=1,3)
  23 DO 901 J=1,3
    TS4MF(L,J)=SUB(2,J)
  901 TS4MF(L,J)=SUB(2,J)
  902 DO 901 J=1,3
    WRITE(6,14) (SUB(3,J),J=1,3)
  903 DO 901 J=1,3
    TS4MF(L,J)=SUB(3,J)
  904 WRITE(6,15) SNGT
  905 WRITE(6,509) SLIF
  906 WRITE(6,501) PDI
  907 WRITE(6,512) SPQY
  908 WRITE(6,503)
  909 WRITE(6,514) SPX,SPY
  910 WRITE(6,505) SPSW
  911 WRITE(6,506) SPSSA
  912 IF (ISCAC-2) 507,508,509
  507 WRITE(6,510)
  508 DO 513
  509 WRITE(6,511)
  510 DO 513
  511 WRITE(6,512) SCENGT
  512 WRITE(6,514) SCFDE
  513 WRITE(6,515) SCFDE
  514 WRITE(6,516)
  515 IF (ISCAC-2) 517,518,519
  517 WRITE(6,520) SCFY,SCBZ,SCRX
  518 DO 523
  519 WRITE(6,521) SCBDA
  520 DO 523
  521 WRITE(6,522) SCBDA,SCBL N
  522 WRITE(6,524) PAXX
  523 WRITE(6,525) SCLMI
  524 WRITE(6,526)
  525 WRITE(6,527)
  526 WRITE(6,528) SP LXX,SP LYY,SP LZZ
  527 IF (ICLHF) 529,530,531

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631 WRITE(6,529) NCT2
630 CONTINUE
WRITE(6,16)
WRITE(6,17)
DO 91 I=1,10
  N=IS(I)
  IF(N)91,91,114
114 GO TO (92,93,95,96,98,99,101,102,104,105),I
92 WRITE(6,18) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
93 WRITE(6,19) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
95 WRITE(6,20) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
96 WRITE(6,21) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
97 WRITE(6,22) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
98 WRITE(6,23) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
101 WRITE(6,24) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
102 WRITE(6,25) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
104 WRITE(6,26) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
105 WRITE(6,27) (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
  GO TO 91
  CONTINUE
  SUMIT
  SUMDV
  N=IACP
  DO 106 I=1,N
106 WRITE(6,28) (C(I,J),J=1,2),SIF(I)
  WRITE(6,33)
  WRITE(6,34)
  DO 107 I=1,N
107 WRITE(6,29) (C(I,J),J=1,2),(IAMP4(I,J),J=1,2),(TWST(I,J),J=1,4)
  WRITE(6,36)

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      WRITE(6,37)
      DO 108 I=1,M
      WRITE(6,38) (C(I,J),J=1,2),(TPIA(I,J),J=1,4)
      IF (ICAMP-1) 109,110,111
      110 WRITE(6,39)
      WRITE(6,40) OPPR,ANZ
      WRITE(6,41)
      WRITE(6,42) PTKCI,PTDIA
      GO TO 111
      109 WRITE(6,43)
      111 WRITE(6,44)
      WRITE(6,45)
      WRITE(6,46) (TOTSUM(I),I=1,4)
      IF (M) 805,805,806
      805 GO 801 I=1,4
      801 ATSUM(I)=0.0
      802 GO 802 I=1,4
      802 ATSUM(I)=AGT(I(I))+TOTSUM(I)
      WRITE(6,46)
      WRITE(6,45)
      WRITE(6,44) (AGT(I),I=1,4)
      WRITE(6,46)
      WRITE(6,45)
      WRITE(6,46) (ATSUM(I),I=1,4)
      CONTINUE
      804 IF (M) 820,820,821
      821 AT(L)=0.0
      803 GO TO 822
      820 AT(L)=ATSUM(I)
      CONTINUE
      IF (L-INCDSTR) 112,113,113
      112 L=L+1
      804 GO TO 47
      113 CONTINUE
      IF (LL(1)) 830,960,931
      830 LL(1)=INCDSTR
      801 N=1
      N=1
      803 KXKK=M+LL(N)-1
      KX=M+LL(N)-2

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```

WRITE(6,981)
WRITE(6,980) SLIFLL(M)
WRITE(6,98) SWSTLL(N)
IF(ISLLE(N)-2)984,987,989
983 WRITE(6,910)
GO TO 989
987 WRITE(6,911)
GO TO 989
989 WRITE(6,912)
989 WRITE(6,982)
IF(ISLLE(M,1))983,983,984
984 WRITE(6,985)
983 IF(ISLLE(M,2))990,990,991
991 WRITE(6,992)
990 IF(ISLLE(M,3))993,993,994
994 WRITE(6,995)
993 IF(ISLLE(M,4))996,996,997
997 WRITE(6,998)
990 IF(ISLLE(M,5))999,999,1000
1000 WRITE(6,1001)
999 IF(ISLLE(M,6))1002,1002,1003
1003 WRITE(6,1004)
1004 IF(ISLLE(M,7))1005,1005,1006
1006 WRITE(6,1007)
1005 IF(ISLLE(M,8))1008,1008,1009
1009 WRITE(6,1010)
1008 IF(ISLLE(M,9))1011,1011,1012
1012 WRITE(6,1013)
1011 IF(ISLLE(M,10))1014,1014,1015
1015 WRITE(6,1016)
1014 CONTINUE
IF(LL(N)-1)964,964,965
965 GO TO 960 I=A, KK
KKK=I+1
DO 960 J=KKK, KKKK
IF(WT(I)-WT(J))950,950,951
951 XXX=WT(I)
WT(I)=WT(J)
WT(J)=XXX
XXX=STOV(I)

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```

STDV(I)=STDV(J)
STDV(J)=XXX
XX=STIMP(I)
STIMP(I)=STIMP(J)
STIMP(J)=XX
DO 952 L=1,3
952 XXX(L)=TLNAME(I,L)
DO 953 L=1,3
953 TLNAME(I,L)=TLNAME(J,L)
DO 954 L=1,3
954 TLNAME(J,L)=XXX(L)
DO 955 L=1,3
955 XXX(L)=TLNAME(I,L)
DO 956 L=1,3
956 TSNAME(I,L)=TSNAME(J,L)
DO 957 L=1,3
957 TSNAME(J,L)=XXX(L)
958 CONTINUE
959 WRITE(6,903)
904 IF(LL(N)-33)904,904,905
904 DO 907 I=5,KKK
905 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STIMP(I),STDV(I)
DO 914
905 AN=P+32
DO 908 I=N,NM
908 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STIMP(I),STDV(I)
WRITE(6,903)
NM=P+33
IF(LL(N)-66)909,909,910
909 DO 911 I=NM,KKK
911 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STIMP(I),STDV(I)
DO 914
910 NM=N+65
DO 912 I=NM,NMN
912 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STIMP(I),STDV(I)
WRITE(6,903)

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```

NNNN=M+66
DO 913 I=NNNN,KKK
  13 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STMP(I
    1),STDV(I)
  14 CONTINUE
  M=M+LL(N)
  N=N+1
  IF(LL(N))962,962,963
  902 CONTINUE
  CALL EXIT
  END
      ACS
ENTRY
$IPSYS

```

## REFERENCES

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